The Physiological Response to Brief Maximal Intermittent Exercise: with Particular Reference to Testing Procedures and Performance Determinants.

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PhD Thesis
University of Edinburgh
2003

DECLARATION

I hereby declare that the composition of this thesis and all the work contained within is entirely my own work.

ABSTRACT

Purpose: The activity patterns of many sports are intermittent in nature, fluctuating randomly from brief periods of maximal or near maximal work to longer periods of moderate and low intensity activity. Attempts to examine the complex energy demands of this type of work have typically utilised repeated bouts of brief (≤ 6-s) maximal work interspersed with relatively short (≤ 60-s) recovery periods. However, despite years of research, many issues concerning the physiological response to this type of activity remain unresolved. The principal aim of the present thesis was to focus on one of these issues, namely the influence of aerobic fitness on sport-specific repeat sprint ability. **Methods:** Physically active students from the University of Edinburgh were used in all studies. Each investigation utilised two distinct maximal intermittent (20 x 5-s) test protocols with contrasting recovery periods (10-s or 30-s). The protocols were designed to simulate the range of work to rest ratios often experienced in sports such as badminton, rugby, soccer, and squash. All tests were conducted on a friction-braked cycle ergometer. **Results:** Both of the intermittent test protocols were found to have good degrees of test-retest reliability in measures of power output and fatigue. Moreover, the highest degrees of test-retest reliability were found to occur after the administration of two familiarisation trials. Although the quantification of fatigue during intermittent work had received a number of different approaches, the percentage decrement score was determined as the most valid and reliable means of assessing this parameter. Differences in recovery duration between the two intermittent test protocols had considerable effects on measures of maximum power output, mean power output, blood lactate, and fatigue. Between-protocol differences in maximum power output were attributed to the potentiation effect associated with Protocol 2 (30-s rest periods). In contrast, differences in mean power output, blood lactate and fatigue were most likely the result of between-protocol differences in the magnitude of the phosphocreatine (PCr) contribution to each sprint. Relative to controls, training-induced improvements in aerobic fitness, as evidenced by a 10.2% increase in $\dot{V}O_{2max}$, corresponded with substantial improvements in intermittent performance measures of maximum and mean power output (range: 3.2 to 8.2%). Endurance training also impacted on the ability to resist fatigue, the magnitude of which increased with increasing recovery duration. Correlations between $\dot{V}O_{2max}$ and fatigue were also dependent on recovery duration supporting the idea that the principle role of aerobic metabolism during brief maximal intermittent work is in the

restoration of homeostasis during intervening rest periods. **Conclusions:** The ability to produce and maintain high power outputs during prolonged periods of brief maximal intermittent work is an important determinant of performance in many sports. The results of the present thesis demonstrate the considerable influence of aerobic fitness in this respect, the magnitude of the effects being largely determined by the duration of the intervening rest periods. Although the precise mechanisms of action require further investigation, the improvements in repeat sprint performance that accompany increases in aerobic fitness are likely to be the result of enhancements in the recovery of power output via improved off-transient inorganic phosphate and PCr kinetics.

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LIST OF ABBREVIATIONS

$\leq$	Less than or equal to
$\geq$	Greater than or equal to
$<$	Less than
$>$	Greater than
$\sim$	Approximately
^{1}H	Magnetic isotope of hydrogen
^{31}P	Magnetic isotope of phosphorous
ADP	Adenosine diphosphate
AMP	Adenosine monophosphate
ATP	Adenosine triphosphate
$b.min^{-1}$	Beats per minute
Ca^{2+}	Calcium ion
CL	Confidence limits
CO_2	Carbon dioxide
Cr	Creatine
CV	Coefficient of variation
dm	Dry muscle
H^+	Hydrogen ion
H_2O	Water
Hz	Hertz
ICC	Intraclass correlation coefficient
IMP	Inosine monophosphate
K^+	Potassium ion
kg	Kilograms
l	Litres
m	Metres
MAOD	Maximal accumulated oxygen deficit
Mb	Myoglobin
min	Minute
ml	Millilitres
mmol	Millimols
MP	Mean power
MP_{max}	Maximum mean power
MP_{mean}	Mean mean power
Na^+	Sodium ion
$NaHCO_3$	Sodium bicarbonate
NH_4^+	Ammonium ion

O_2	Oxygen
O_2eq	Oxygen equivalents
p	Probability
PCr	Phosphocreatine
PDH	Pyruvate dehydrogenase
PFK	Phosphofructokinase
pH	Power of hydrogen ion concentration
P_i	Inorganic phosphate
PP	Peak power
PP_{max}	Maximum peak power
PP_{mean}	Mean peak power
r	Correlation coefficient
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
rpm	Revolutions per minute
s	Seconds
SD	Standard deviation
SR	Sarcoplasmic reticulum
$\dot{V}CO_2$	Rate of carbon dioxide production
$\dot{V}O_2$	Rate of oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
W	Watts
W:R	Work to rest ratio

ACKNOWLEDGEMENTS

I will forever be indebted to the following for their contribution towards the completion of this thesis: the University of Edinburgh Department of PE, Sport & Leisure studies and the University of Edinburgh Development Trust for funding the research contained within this thesis; Ian Hamilton and Dr Simon Coleman for their technical expertise in helping me to develop the intermittent sprint tests; all of the students who volunteered to put themselves through the demanding testing procedures involved in this thesis; Allison, Annette, Gemma, Hugh, Javi, Lynne, and Rosie for their help in administering the tests; all my friends and family for their unceasing support throughout this entire journey; Mike Hughes for all his help as my unofficial third supervisor; Gavin for tolerating my constant ramblings on the wonders of my research; Dr Andrew Stewart for all his help as my second supervisor; and Professor Mike Stone without who's help and support none of the research contained within this thesis would have been possible.

Dedicated to Patricia Glaister (1926 – 1988) and Martin Whittingham (1962 – 2002).

1. INTRODUCTION

Pioneering research into intermittent exercise began over 40 years ago with many studies investigating the physiological response to this type of work using a wide range of methodologies. More recently, advances in time-motion analysis techniques have led several investigations to focus on the type of intermittent work experienced in many sports (e.g. badminton, basketball, hockey, rugby, soccer, and squash). These studies have typically investigated brief (≤ 6-s) bouts of maximal work interspersed with relatively short (≤ 60-s) recovery periods. Although laboratory-based studies of intermittent exercise differ considerably from the irregular activity patterns experienced in the field, they currently provide the best means of directly assessing the physiological response to this type of work. Despite this observation, the interactions between the various metabolic processes that regulate the physiological response to maximal intermittent work remain largely unresolved.

During a single short (≤ 6-s) maximal sprint, adenosine triphosphate (ATP) is resynthesised predominantly from anaerobic sources (phosphocreatine (PCr) degradation and glycolysis) (Bangsbo *et al.*, 2001; Boobis *et al.*, 1982; Gaitanos *et al.*, 1993; Hultman *et al.*, 1990; Hultman *et al.*, 1991), with a minimal contribution (approximately 5 to 10%) from aerobic metabolism (Bangsbo *et al.*, 2001; Parolin *et al.*, 1999). During recovery, oxygen consumption ($\dot{V}O_2$) remains elevated to restore homeostasis via processes such as the replenishment of tissue O_2 stores, the resynthesis of PCr, the metabolism of lactate, and the removal of intracellular inorganic phosphate (P_i). If recovery periods are relatively short, as in many sporting events, $\dot{V}O_2$ remains elevated prior to subsequent sprints and the aerobic contribution to ATP resynthesis increases (Bogdanis *et al.*, 1998; Gaitanos *et al.*, 1993; Hamilton *et al.*, 1991). However, if the duration of recovery periods is insufficient to restore the metabolic environment to resting conditions, performance during successive work bouts may be compromised.

The substantial aerobic contribution to maximal sport-specific intermittent work, particularly during recovery periods, has prompted several authors to propose a possible link between aerobic fitness and intermittent exercise performance (Aziz *et al.*, 2000; Balsom, 1995; Bell *et al.*, 1997; Bogdanis *et al.*, 1996; Cooke *et al.*, 1997; Dawson *et al.*, 1993; Tomlin &

Wenger, 2001). However, whilst the theoretical basis for such a relationship is compelling, corroborative research is far from substantive.

Studies examining the influence of endurance training on the recovery processes of PCr resynthesis (Bogdanis *et al.*, 1996; Cooke *et al.*, 1997; Laurent *et al.*, 1992; McCully *et al.*, 1989; Takahashi *et al.*, 1995; Yoshida & Watari, 1993) and lactate removal (Bassett *et al.*, 1991; Fukuba *et al.*, 1999; Oosthuyse & Carter, 1999; Oyono-Enguelle *et al.*, 1990; Taoutaou *et al.*, 1996) have yielded conflicting results. Inconsistencies also exist in the results of correlational analyses between maximal oxygen uptake ($\dot{V}O_{2max}$) and various intermittent exercise performance indices (Aziz *et al.*, 2000; Bishop *et al.*, 1999; Dawson *et al.*, 1993; Wadley & Le Rossignol, 1998). Although methodological differences may account for some of the discrepancies, the influence of protocol variation on the magnitude of those discrepancies is at present unknown.

All in all, despite years of research, many issues concerning the physiological response to repeated bouts of brief maximal work remain unresolved. The principle aims of the present thesis were to address a number of these issues by investigating: a) the influence of aerobic fitness on various maximal sport-specific intermittent exercise performance indices and; b) the influence of recovery duration on the magnitude of those responses. To fulfil these aims, the following series of investigations were conducted:

- Study I investigated the number of familiarisation trials required to establish high degrees of test-retest reliability in measures of power output during two distinct brief maximal intermittent sprint cycling protocols.

- Study II investigated the reliability and validity of the various methods used to assess fatigue during brief maximal intermittent work.

- Study III examined the influence of recovery duration on various performance measures of brief maximal intermittent work.

- Study IV examined how the physiological variables of $\dot{V}O_{2max}$ and anaerobic capacity correlated with several indices of brief maximal intermittent work.

- Study V examined the effects of 6-weeks of endurance training on brief maximal intermittent performance.

Two distinct maximal intermittent sprint cycling test protocols were used for the studies. The protocols were designed to simulate the range of work to rest ratios (W:R) often experienced in sports such as badminton (Docherty, 1982; Liddle *et al.*, 1996), soccer (Mayhew & Wenger, 1985; Reilly, 1997), rugby (Brewer & Davis, 1995; Docherty *et al.* 1988), and squash (Docherty, 1982; Montpetit, 1990).

2. LITERATURE REVIEW

2.1 Activity Profiles of Multiple Sprint Sports

The activity patterns of many sports are intermittent in nature, fluctuating randomly from brief periods of maximal or near maximal work to longer periods of moderate and low intensity activity. The duration of these events is often greater than an hour and in the case of team sports (basketball, hockey, rugby, soccer, etc.), activity patterns are considerably influenced by player position (Bangsbo *et al.*, 1991b; Brewer & Davis, 1995; Docherty *et al.*, 1988; Ekblom, 1986; Reilly & Thomas, 1976; Withers *et al.*, 1982).

In field sports (hockey, rugby, soccer, etc.), distances covered during games range from 5,000 to 11,000 m depending on player position, skill level, and game duration (Bangsbo *et al.*, 1991b; Brewer & Davis, 1995; Reilly & Borrie, 1992). The percentages of game-time spent in various forms of locomotion are difficult to quantify due to methodological differences between studies. However, the mean duration of high-intensity efforts is reported be approximately 4 to 7-s (Bangsbo *et al.*, 1991b; Docherty *et al.*, 1988; Mayhew & Wenger, 1985; Withers *et al.*, 1982), of which approximately 2-s is attributed to sprinting (Bangsbo *et al.*, 1991b; Brodowicz *et al.*, 1990; Docherty *et al.*, 1988). Although the ratio of high-intensity to low-intensity activities range from 1:6 to 1:14 (Bangsbo, 1994; Brewer & Davis, 1995; Nicholas, 1997; Reilly, 1997; Withers *et al.*, 1982), values are clouded by limitations in the various methods used to determine these intensities.

In contrast to field sports, racquet sports (badminton, squash, and tennis), due to the nature of the games, display much more consistent activity patterns. In general, high-intensity efforts (rallies) are on average 5 to 10-s in length depending on playing ability (Christmass *et al.*, 1998; Docherty, 1982; Elliott *et al.*, 1985; Faccini & Dal Monte, 1996; Liddle *et al.*, 1996; Majumdar *et al.*, 1997; Montpetit, 1990), with W:R ranging from 1:1 to 1:5. A summary of the results of several time-motion analyses of racquet sports is presented in Table 2.1.

2.2 Physiological Demands of Multiple Sprint Sports

Research into the physiological demands of multiple sprint sports indicates that these events place considerable demands on both aerobic and anaerobic pathways, although the relative contribution from each of these sources is an issue of some controversy (Christmass *et al.*,

1998; Mayhew & Wenger, 1985; Nicholas, 1997; Reilly & Borrie, 1992). The average physiological response to intermittent sporting events is reported to be similar to that of prolonged continuous exercise, with mean exercise intensities of 60 to 75% $\dot{V}O_{2max}$ (Bangsbo, 1994; Boyle *et al.*, 1994; Christmass *et al.*, 1998; Faccini & Dal Monte, 1996; Montpetit, 1990; Reilly, 1997), and mean heart rates of 70 to 90% of maximum (Christmass *et al.*, 1998; Docherty, 1982; Ekblom, 1986; Elliott *et al.*, 1985; Faccini & Dal Monte, 1996; Liddle *et al.*, 1996; Montpetit, 1990). However, expressing intensity as an average value during a game is likely to mask the complexity of the physiological processes that regulate this type of activity. Moreover, field-based physiological assessments of multiple sprint sports have several limitations.

Table 2.1 Typical work to rest ratios experienced in racquet sports.

Author	Sport	Subject Group	Mean Rally Time (s)	Work to rest ratio
Docherty (1982)	Squash	Range of abilities	4.4 – 8.8	1:1
Montpetit (1990)	Squash	Range of abilities	6.9 – 16.6	1:1
Docherty (1982)	Badminton	Range of abilities	4.2 – 4.9	1:2
Faccini & Dal Monte (1996)	Badminton	National level	7.4	1:2
Majumdar *et al.* (1997)	Badminton	National level	4.6	1:2
Christmass *et al.* (1998)	Tennis	State level	10.2	1:1.7*
Docherty (1982)	Tennis	Range of abilities	4.0 – 4.3	1:5
Elliott *et al.* (1985)	Tennis	College level	10.0	1:1.8*

Note: * Does not include time spent changing ends.

Direct field-based assessments of $\dot{V}O_2$ are confounded by the inhibitory effects of the portable devices currently available for this type of assessment. Furthermore, this type of assessment is only feasible in simulated matchplay. One way to address this problem has been to assess $\dot{V}O_2$ from heart rate data using laboratory determined submaximal heart rate-$\dot{V}O_2$ relationships. However, heart rate-$\dot{V}O_2$ relationships can be compromised during intermittent work due to factors such as emotional stress, elevated levels of catecholamines, and the accumulation of various metabolic by-products (Bangsbo, 1994; Ballor & Volovsek, 1992; Christmass *et al.*, 1998; Faccini & Dal Monte, 1996).

Field-based assessments of blood lactate are often used as an indication of anaerobic lactacid ATP production. However, blood lactate levels are only a reflection of the balance between lactate production and clearance. Furthermore, sampling times are restricted to natural breaks in matches or disruptions to standard match conditions and only reflect the level of activity during the few minutes prior to sampling. Although field-based assessments of blood lactate during multiple sprint sports generally report relatively low mean values of between 2 and 5 $mmol.l^{-1}$ (Bangsbo *et al.*, 1991b; Bangsbo, 1994; Bergeron *et al.*, 1991; Docherty *et al.*, 1988; Faccini & Dal Monte, 1996; Majumdar *et al.*, 1997; Montpetit, 1990), peak values as high as 10 $mmol.l^{-1}$ have been recorded (Reilly, 1997).

The limitations associated with field-based investigations of intermittent sporting activities have led many researchers to investigate this type of work in a laboratory setting (Balsom, 1995; Brooks *et al.*, 1990; Christmass *et al.*, 1999; Gaitanos *et al.*, 1993; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988). These studies have typically examined brief (≤ 6-s) bouts of maximal work interspersed with relatively short (≤ 60-s) recovery periods. Although laboratory based investigations of intermittent work differ considerably from the activity patterns experienced in the field, they currently provide the best means of directly assessing the physiological response to this type of work. Before reviewing research into the metabolic factors that may limit performance, it is important to consider the complex energetics associated with this type of work.

2.3 The Energetics of Brief Maximal Work

2.3.1 Adenosine Triphosphate

Energy for muscular work is obtained from the hydrolysis of ATP.

$$ATP \underset{ATPase}{\rightleftharpoons} ADP + P_i + Energy$$

The human body typically stores within muscle approximately 20 – 25 mmol.kg dry muscle $(dm)^{-1}$ of ATP which, with peak ATP turnover rates of approximately 15 $mmol.kg\ dm^{-1}.s^{-1}$, is enough to fuel 1 – 2 seconds of maximal work (Bogdanis *et al.*, 1998; Gaitanos *et al.*, 1993; Parolin *et al.*, 1999). As the store of ATP becomes depleted, ATP for continued muscular work is resynthesised by the integration of various metabolic processes.

2.3.2 Phosphocreatine

Phosphocreatine (PCr) is particularly important during explosive activities when a high rate of energy release is required. The resynthesis of ATP is driven by the reaction between PCr and adenosine diphosphate (ADP). The reaction is catalysed by the enzyme creatine kinase and results in the formation of ATP and free creatine (Cr).

$$PCr + ADP + H^{+} \underset{\text{Creatine Kinase}}{\rightleftharpoons} ATP + Cr$$

Intramuscular PCr stores total approximately 80 mmol.kg dm^{-1} (Bangsbo *et al.*, 2001; Bogdanis *et al.*, 1998; Gaitanos *et al.*, 1993; Parolin *et al.*, 1999). During maximal work, PCr degradation follows an exponential pattern of decay (Figure 2.1) with maximal turnover rates of approximately 9 mmol ATP.kg $dm^{-1}.s^{-1}$ (Hultman & Sjöholm, 1983), largely depleting stores within 10-s.

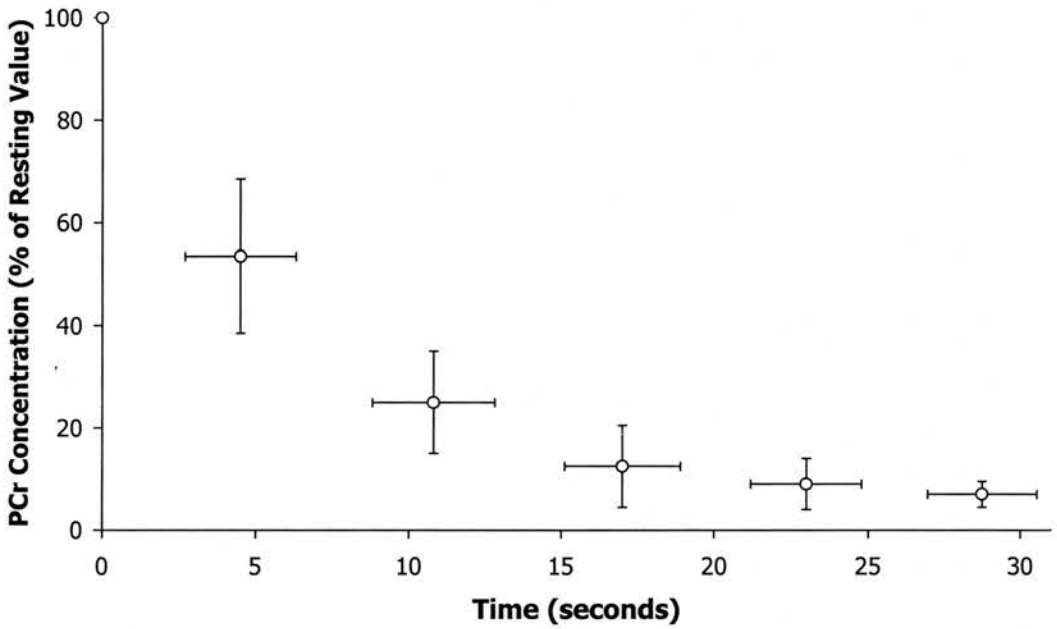


Figure 2.1 PCr kinetics of the medial gastrocnemius during 30-s of repeated maximal plantar flexions of the foot determined from localised nuclear magnetic resonance imaging. Open circles represent PCr as a percentage of resting values; bars represent standard deviations. Re-drawn from: Walter *et al.* (1997).

2.3.3 Anaerobic Glycolysis

Anaerobic glycolysis involves the breakdown of glucose, mainly in the form of muscle glycogen, to ATP and lactate.

$$\text{Glycogen} + 3\ \text{ADP} + 3\ P_i \longrightarrow 3\ \text{ATP} + 2\ \text{Lactate}^- + 2\ H^+$$

ATP production from anaerobic glycolysis is activated rapidly at the onset of maximal work reaching peak rates of around 6 to 9 mmol ATP.kg $dm^{-1}.s^{-1}$ (Hultman *et al.*, 1990; Hultman & Sjöholm, 1983; Jones *et al.*, 1985; Parolin *et al.*, 1999) after approximately 5 seconds (Gastin, 2001; Greenhaff *et al.*, 1996).

2.3.4 Aerobic Metabolism

During maximal work, aerobic ATP resynthesis is achieved primarily through the oxidation of glucose (Bangsbo *et al.*, 1992a; Bangsbo *et al.*, 2001).

$$C_6H_{12}O_6\ (\text{glucose}) + 6O_2 + 38\ \text{ADP} + 38\ P_i \longrightarrow 6CO_2 + 6H_2O + 38\ \text{ATP}$$

It is difficult to accurately assess the aerobic contribution to a short bout of maximal work due to methodological problems associated with a) assessing the $\dot{V}O_2$ of the working muscles; b) determining the size of the active muscle mass; and c) evaluating the contribution of oxygen released from myoglobin. During the first 6-s of a 30-s maximal sprint the mean rate of aerobic ATP turnover has been estimated at 1.32 mmol ATP.kg $dm^{-1}.s^{-1}$ (approximately 9% of the total energy produced) (Parolin *et al.*, 1999).

2.3.5 The Adenylate Kinase Reaction

During intense periods of work, when the required rate of ATP provision cannot be maintained by the above energy pathways, ATP can be generated from pairs of ADP molecules. The reaction is catalysed by the enzyme adenylate kinase and results in the formation of ATP and adenosine monophosphate (AMP).

$$\text{ADP} + \text{ADP} \underset{\text{Adenylate Kinase}}{\rightleftharpoons} \text{ATP} + \text{AMP}$$

Adenosine monophosphate is further deaminated to Inosine monophosphate (IMP) and ammonia in a reversible reaction catalysed by the enzyme AMP deaminase.

$$AMP + H^{+} \underset{\text{AMP Deaminase}}{\rightleftharpoons} IMP + NH_4^{+}$$

Although these reactions may temporarily reduce the availability of adenine nucleotides for phosphorylation, the majority are resynthesised during recovery via the purine nucleotide cycle. Moreover, high-intensity training is reported to reduce the loss of adenine nucleotides during intense exercise (Hellsten-Westing *et al.*, 1993).

2.3.6 Summary

During brief periods of maximal work ATP provision is maintained through the complex integration of various metabolic processes. These processes work together to achieve peak ATP turnover rates of around 15 mmol ATP.kg $dm^{-1}.s^{-1}$. However, as work bouts are repeated, as in many team sports, the metabolic response to subsequent work bouts is dependent on the duration of the intervening rest periods.

2.4 The Physiology Of Brief Maximal Intermittent Work

2.4.1 Introduction

Early investigations into the physiology of short bouts (≤ 10-s) of intermittent work suggested that the ATP required to fuel contractile activity was derived predominantly from aerobic metabolism (Astrand *et al.*, 1960; Christensen *et al.*, 1960). The theoretical basis for this conclusion was that oxygen bound to myoglobin offset the usual oxygen deficit that accompanies any bout of work. This store would be replenished during each recovery period thereby enabling a greater aerobic contribution to overall energy production. However, the intensities of the work bouts used were considerably less than maximal.

In contrast, Margaria *et al.* (1969), using intensities sufficient to exhaust subjects within 30 to 40 seconds of continuous treadmill running, suggested that with sufficient recovery (≥ 25-s) the ATP required to fuel 10-s bouts of 'heavy' intermittent work was derived predominantly from the degradation of PCr. However, this conclusion was highly speculative, as PCr was not measured in the study.

It is now accepted that intermittent bouts of brief maximal work are fuelled by the integration of various metabolic pathways. The role of these pathways during repeated bouts of brief (≤ 6-s) maximal work will be examined in the following sections of this thesis.

2.4.2 Anaerobic Energy Provision during Brief Maximal Intermittent Work

2.4.2.1 *Phosphocreatine*

During a single short (5 to 6-s) maximal sprint, PCr degradation is reported to contribute to approximately 50% of the total anaerobic ATP provision (Boobis et al., 1982; Gaitanos et al., 1993; Parolin et al., 1999). However, the PCr contribution during repeated sprints is largely determined by the extent to which PCr stores are replenished during the intervening recovery periods.

The recovery kinetics of PCr have been examined *in vivo* (using ^{31}P magnetic resonance spectroscopy) and *in vitro* (using muscle biopsies) in several investigations (Blei *et al.*, 1993; Bogdanis *et al.*, 1995; Cooke *et al.*, 1997; Harris *et al.*, 1976; Haseler *et al.*, 1999; McCann *et al.*, 1995; McCreary *et al.*, 1996; McCully *et al.*, 1994; Nevill *et al.*, 1997; Paganini *et al.*, 1997; Quistorff *et al.*, 1992; Roussel *et al.*, 2000; Sahlin *et al.*, 1979; Takahashi *et al.*, 1995; Thompson *et al.*, 1995; Walter *et al.*, 1997). The consensus of opinion appears to be that PCr recovery kinetics are extremely complex, as reflected by large individual and between-protocol differences.

Analyses of PCr recovery kinetics under ischaemic conditions have demonstrated that PCr resynthesis is achieved exclusively via aerobic ATP resynthesis (Blei *et al.*, 1993; Harris *et al.*, 1976; Quistorff *et al.*, 1992; Sahlin *et al.*, 1979). Moreover, PCr recovery kinetics have been shown to be sensitive to manipulations of oxygen availability (Haseler *et al.*, 1999; Idström *et al.*, 1985) (Figure 2.2).

After submaximal work, with minimal disruption to pH, PCr follows a monoexponential pattern of resynthesis (Figure 2.2), the time/rate constants of which are reported to provide an index of oxidative capacity (Takahashi *et al.*, 1995; Thompson *et al.*, 1995). However, following maximal work, PCr recovery kinetics are best described by a biexponential pattern of resynthesis (Figure 2.3), the initial fast phase of which is reported to be largely unaffected by the concomitant drop in pH (Roussel *et al.*, 2000; Sahlin *et al.*, 1979; Walter *et al.*, 1997).

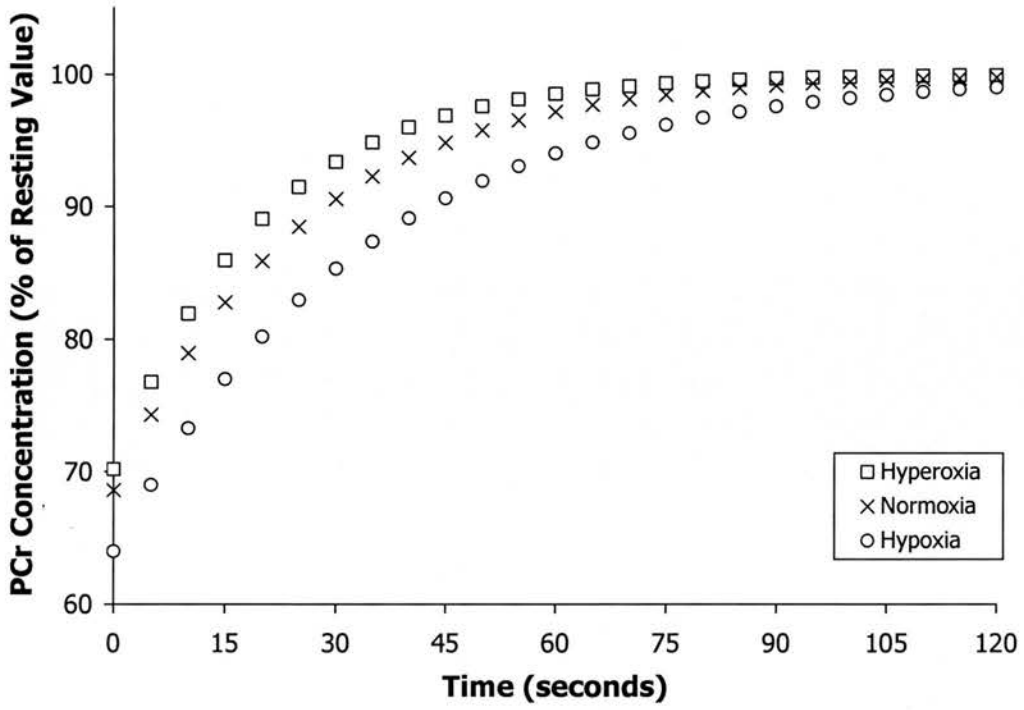


Figure 2.2 Phosphocreatine recovery kinetics of the gastrocnemius following five minutes of repeated submaximal plantar flexions of the foot determined from localised nuclear magnetic resonance imaging. Data from: Haseler *et al.* (1999).

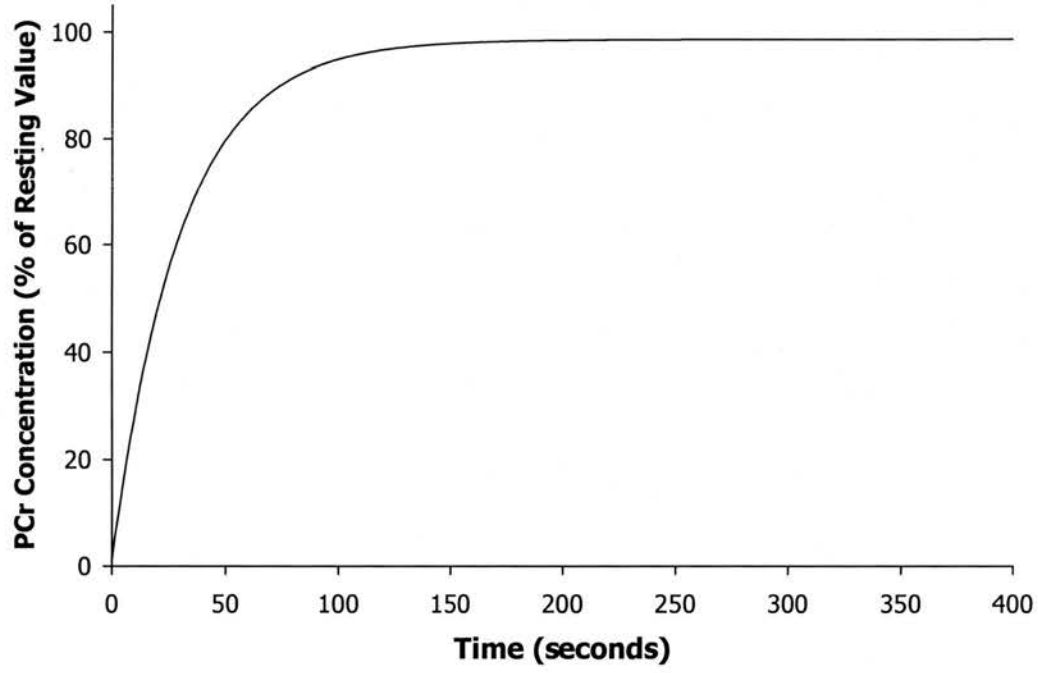


Figure 2.3 PCr recovery kinetics of the medial gastrocnemius following 30-s of repeated maximal plantar flexions of the foot determined from localised nuclear magnetic resonance imaging. Re-drawn from: Walter *et al.* (1997).

Information on the influence of recovery duration on PCr resynthesis during short-duration maximal intermittent work is sparse due to the invasive nature of muscle biopsy procedures and the fact that ^{31}P magnetic resonance spectroscopy techniques cannot as yet be used to examine the large muscle masses involved in sprint work. However, using 10 x 6-s maximal sprints (cycle ergometer), Gaitanos *et al.* (1993) reported that 30-s recovery periods enabled PCr to make a substantial contribution (approximately 25 to 45 mmol ATP.kg dm^{-1}) to ATP resynthesis throughout each sprint. Moreover, despite a progressive decline in the pre-sprint concentration of PCr throughout each trial, it is likely that with resynthesis rates of around 1.3 mmol.kg $dm^{-1}.s^{-1}$, 30-s recovery periods would have enabled PCr to continue to make a substantial contribution to total ATP resynthesis beyond the final sprint.

2.4.2.2 *Glycolysis*

During a brief maximal sprint, the rapid drop in PCr concentration is offset by the increased activation of glycolysis with the two processes combining to maintain ATP turnover at a rate of 11 to 14 mmol ATP.kg $dm^{-1}.s^{-1}$ (Boobis *et al.*, 1982; Gaitanos *et al.*, 1993). At high glycolytic rates, muscle lactate increases to extremely high levels and the associated increase in hydrogen ion (H^+) concentration is often implicated as a cause of fatigue (Bergström & Hultman, 1991; Hultman *et al.*, 1991; Metzger & Fitts, 1987; Roberts & Smith, 1989; Sahlin, 1992; Sahlin *et al.*, 1998). During recovery, glycolysis is reportedly switched off (Quistorff *et al.*, 1992; Sahlin *et al.*, 1990; Taylor *et al.*, 1983) and the return of pH to resting levels follows a monoexponential pattern of resynthesis (Figure 2.4) with a half-time of approximately 9 minutes (Metzger & Fitts, 1987; Sahlin *et al.*, 1976).

The rate of glycolytic ATP provision is regulated by the intricate interplay between many metabolic factors (Figure 2.5). During maximal intermittent work, progressive changes in the metabolic environment lead to a gradual inhibition of glycolysis with repeated sprints (Bangsbo, 1996; Gaitanos *et al.*, 1993; McCartney *et al.*, 1986; Parolin *et al.*, 1999; Putman *et al.*, 1995; Spriet *et al.*, 1989). For example, in the study by Gaitanos *et al.* (1993), glycolysis accounted for 44% of the total anaerobic ATP provision during the first sprint, whilst the corresponding value for the 10^{th} sprint was 16% (Figure 2.6). Moreover, in 4 of the subjects (n = 7), the glycolytic contribution to total anaerobic ATP production during the 10^{th} sprint was estimated to be zero.

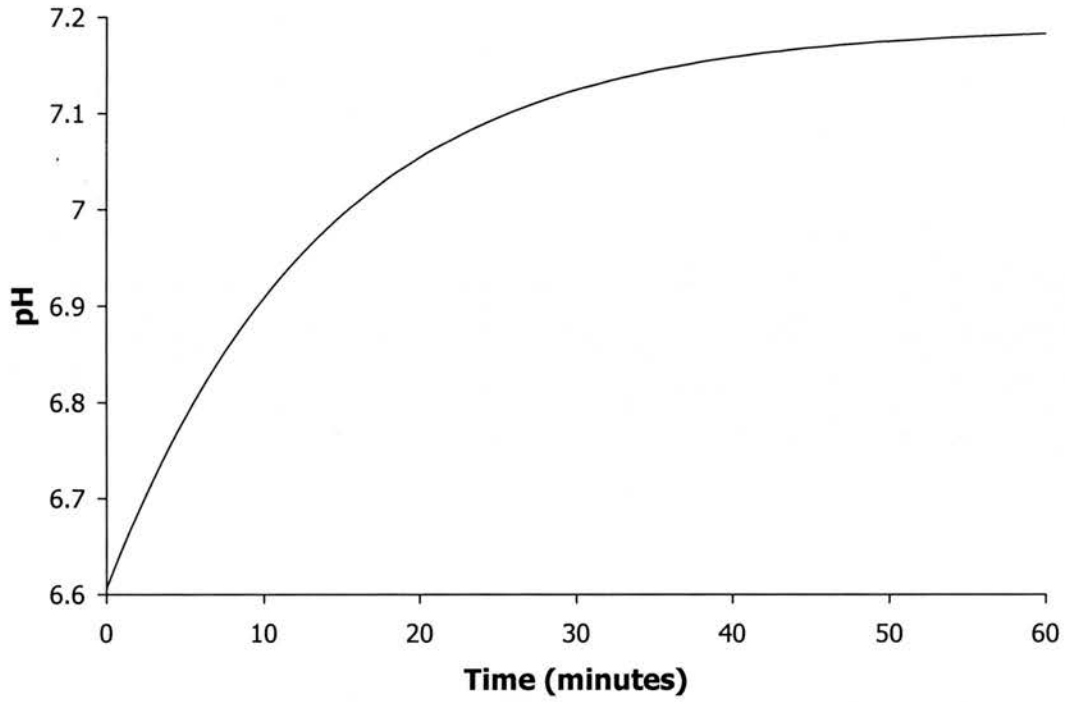
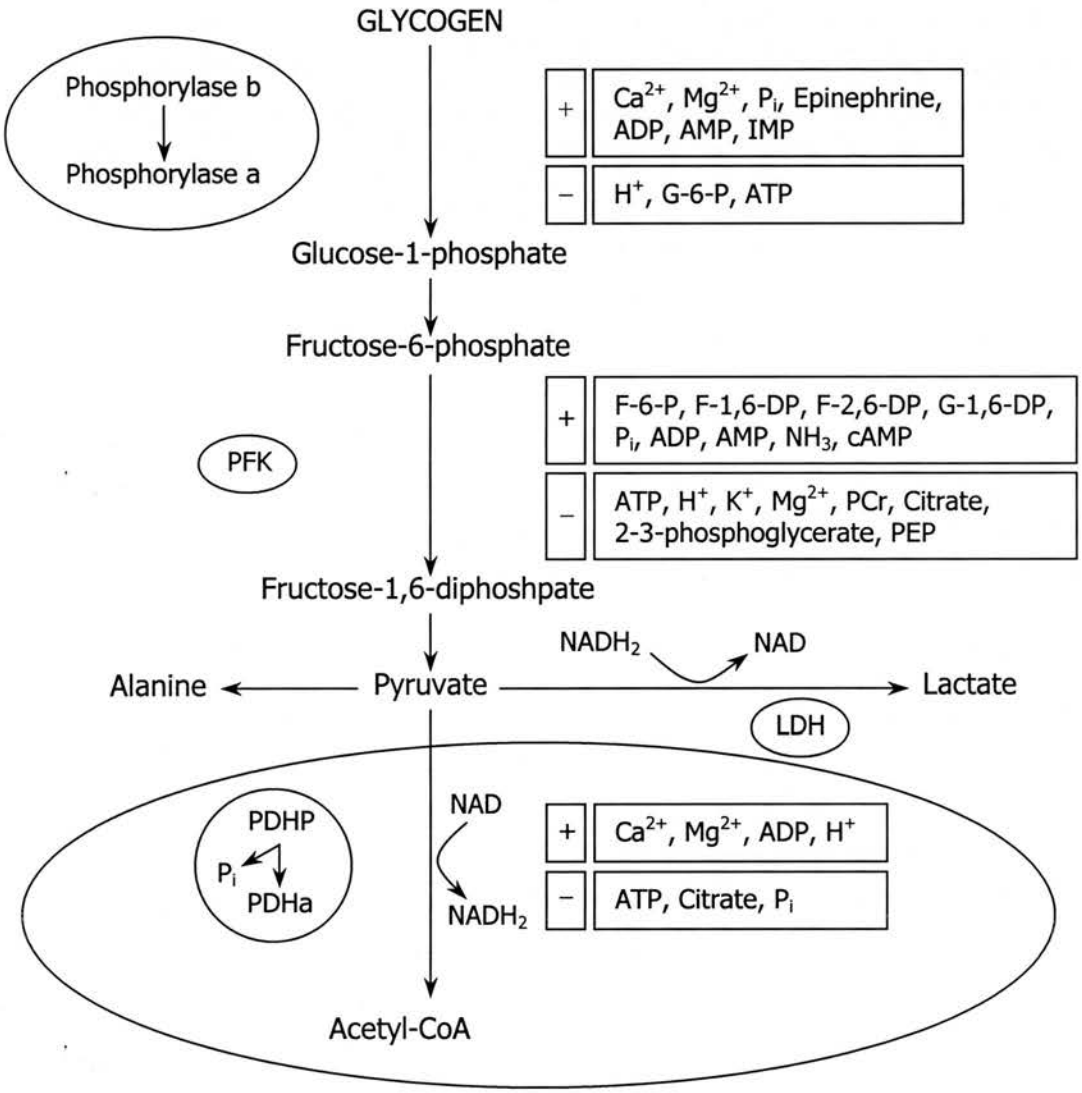


Figure 2.4 Time course of muscle pH during passive recovery from six minutes of exhaustive dynamic exercise. From Sahlin *et al.* (1976).

Various mechanisms have been postulated to account for the inhibition of glycolysis with repeated sprints (Bangsbo, 1996). One suggestion is that glycolysis is impaired by the progressive depletion of muscle glycogen stores that accompanies this type of work (Balsom *et al.*, 1999; Gaitanos *et al.*, 1993). Several studies have reported altered glycolytic rates following glycogen manipulation (Asmussen *et al.* 1974; Greenhaff *et al.*, 1988; Maughan & Poole, 1981). In contrast, several other investigations report contradictory findings (Bangsbo *et al.*, 1992b; Jacobs, 1981; Ren *et al.*, 1990; Spencer & Katz, 1991; Symons & Jacobs, 1989). Another idea is that glycolysis is impaired by the aforementioned progressive drop in pH. An accumulation of H^+ is known to inhibit phosphorylase and phosphofructokinase (PFK), the key regulatory enzymes of glycogenolysis and glycolysis (Boscá *et al.*, 1985). However, the influence of pH on PFK is reported to be negligible within the normal physiologic range (pH $\geq$ 6.4) (Dobson *et al.*, 1986; Spriet *et al.*, 1987). A third possibility is that glycolysis is inhibited by an accumulation of cytosolic citrate, since citrate also exerts an inhibitory effect on PFK (Boscá *et al.*, 1985; Parmeggiani & Bowman, 1963; Passonneau & Lowry, 1963; Taylor & Halperin, 1973; Wu & Davis, 1981). However, the influence of citrate on PFK is reportedly small within the normal physiologic range of 0.1 to 0.3 $mmol.l^{-1}$

(Peters & Spriet, 1995). Although the progressive impairment of glycolysis during repeated maximal sprints may result from the interplay between several regulatory processes, further investigations are required before the precise mechanisms of glycolytic inhibition can be identified.



Note: F-6-P = Fructose-6-phosphate; F-1,6-DP = Fructose-1,6-diphosphate; F-2,6-DP = Fructose-2,6-diphosphate; G-1,6-DP = Glucose-1,6-diphosphate; LDH = Lactate dehydrogenase; NAD = Nicotinamide adenine dinucleotide; PDH = Pyruvate dehydrogenase; PEP = Phosphoenolpyruvate; PFK = Phosphofructokinase.

Figure 2.5 Schematic representation of the anaerobic metabolic pathways of glycogenolysis/glycolysis and a number of potential regulators. Note: + denotes positive regulators; – denotes negative regulators. Re-drawn from: Bangsbo (1996).

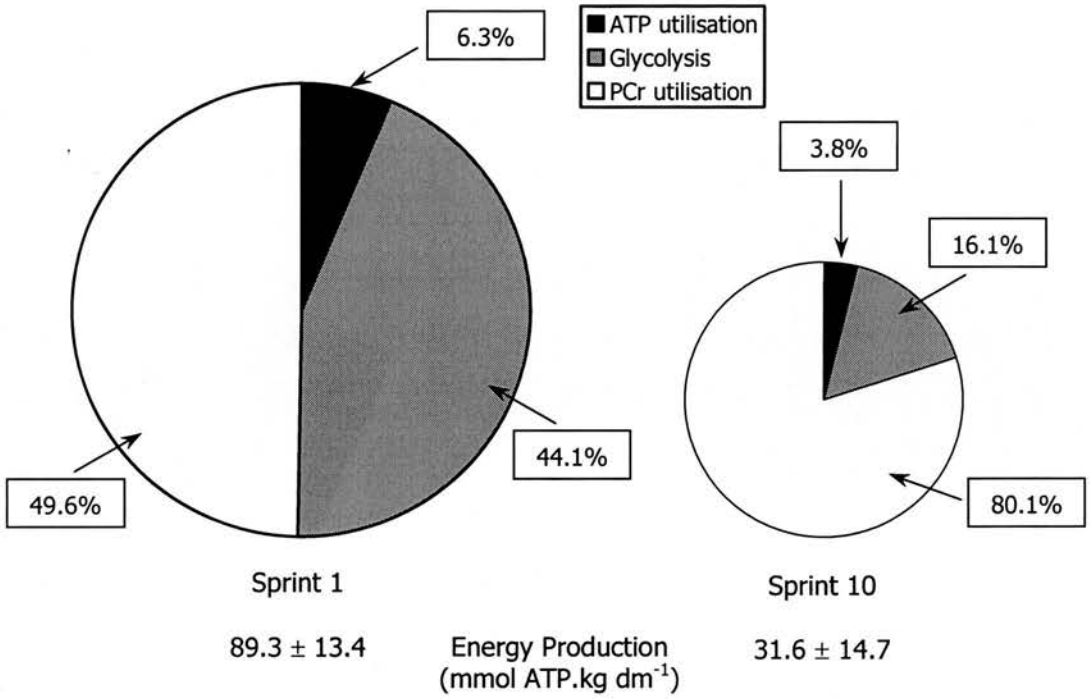


Figure 2.6 Anaerobic ATP production (excluding energy provision related to lactate efflux) during the first and tenth sprints of 10 x 6-s maximal sprints interspersed with 30-s recovery periods. From: Gaitanos *et al.* (1993)

2.4.3 Aerobic Energy Provision during Brief Maximal Intermittent Work

At the onset of a bout of intense work there is a delay in oxygen uptake by the working muscles (Figure 2.7). However, if the duration of the work period is limited to a few seconds, oxygen bound to myoglobin (MbO_2) may buffer the initial oxygen demand of the exercise (Conley *et al.*, 2000; Richardson *et al.*, 2001; Wittenberg *et al.*, 1975).

The MbO_2 content of human skeletal muscle is approximately 2 mmol O_2.kg dm^{-1} (Akeson *et al.*, 1968; Harris *et al.*, 1975). This store of oxygen is rapidly desaturated at the onset of exercise in response to a rapid drop in the intracellular partial pressure of oxygen (Molé *et al.*, 1999; Richardson *et al.*, 1995). At an intensity sufficient to elicit $\dot{V}O_{2max}$, MbO_2 is desaturated to approximately 50% of resting values within 20-s (Molé *et al.*, 1999; Richardson *et al.*, 1995). However, the sensitivity of MbO_2 desaturation to exercise intensity is an issue of some controversy (Molé *et al.*, 1999; Richardson *et al.*, 2001).

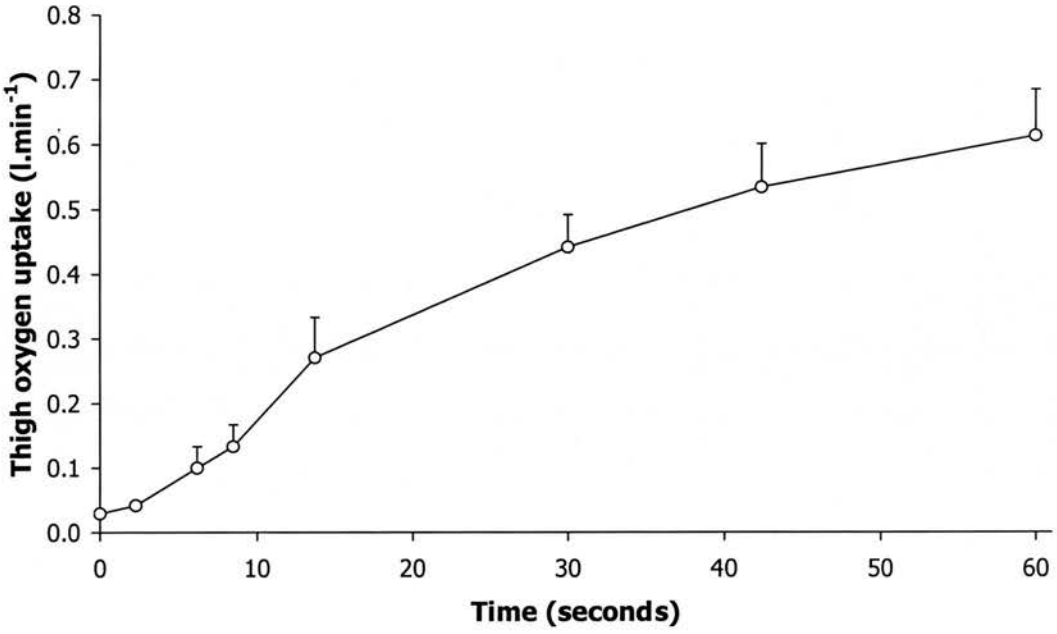


Figure 2.7 Thigh oxygen uptake during the first minute of a 3-minute bout of intense (~ 120% $\dot{V}O_{2max}$) knee-extensor exercise. Note: Values are corrected for blood transit times. From: Bangsbo *et al.* (2000).

During recovery, MbO_2 stores are fully replenished within 20-s of the cessation of exercise (Richardson *et al.*, 1995). With such a rapid rate of resaturation, it is unlikely that the availability of oxygen from myoglobin would be a limiting factor during repeated sprints. However, *in vivo* examinations of myoglobin function by means of ^1H magnetic resonance spectroscopy are a recent development and clearly much more research is required to fully establish the role of myoglobin during single and repeated bouts of maximal work.

Based on the above findings, Bangsbo *et al.* (2001) estimated the mean rate of aerobic ATP turnover during the first 5-s of a three-minute bout of intense (~ 120% $\dot{V}O_{2max}$) exercise to be 0.7 mmol ATP.kg $dm^{-1}.s^{-1}$. This value is in close agreement with the value of 1.3 mmol ATP.kg $dm^{-1}.s^{-1}$ reported by Parolin *et al.* (1999) during the first 6-s of a 30-s maximal sprint and substantiates the minor (< 10%) aerobic contribution to overall ATP resynthesis during a single short maximal sprint. However, as sprints are repeated, the level of aerobic ATP provision is reported to increase progressively due to elevated and accelerated $\dot{V}O_2$ kinetics (Bogdanis *et al.*, 1996; Gaitanos *et al.*, 1993; Parolin *et al.*, 1999; Putman *et al.*, 1995; Spriet *et al.*, 1989; Trump *et al.*, 1996).

During recovery from a bout of high-intensity work, $\dot{V}O_2$ remains elevated for some time in order to restore the metabolic environment to resting conditions through processes such as the replenishment of MbO_2 stores, the resynthesis of PCr, and the metabolism of lactate (Bahr *et al.*, 1992; Bangsbo & Hellsten, 1998; Børsheim *et al.*, 1998; Gaesser & Brooks, 1984). If subsequent sprints are performed before $\dot{V}O_2$ has returned to resting levels, then the $\dot{V}O_2$ of successive sprints will be elevated (Figure 2.8).

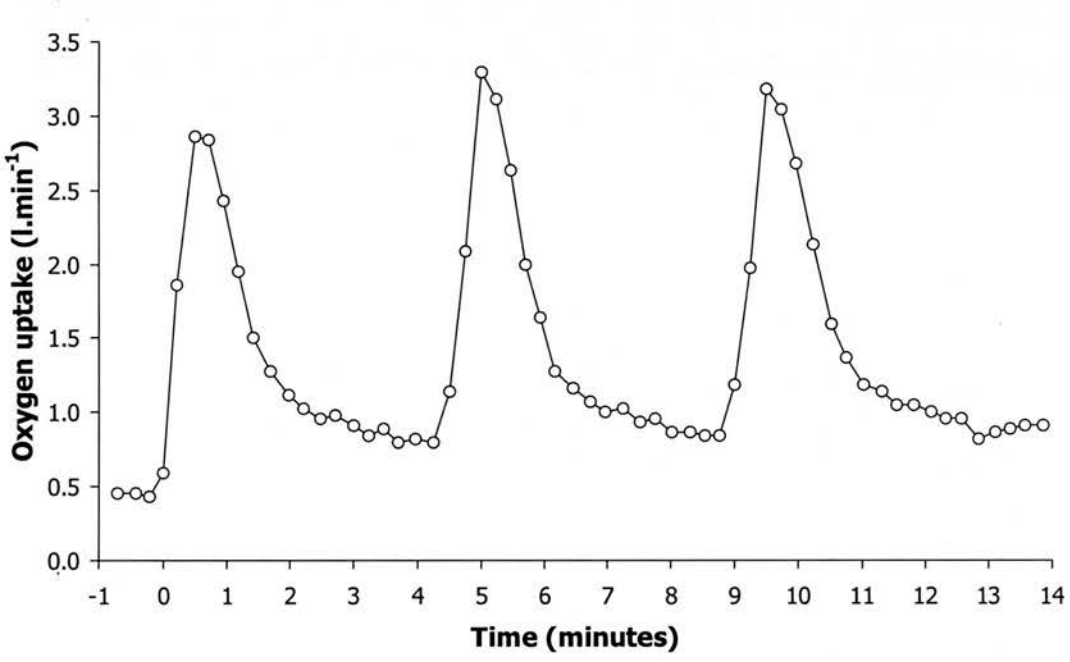


Figure 2.8 Oxygen uptake during 3 x 30-s bouts of maximal isokinetic cycling separated by 4-minute recovery periods. From: Putman *et al.* (1995).

The elevation in $\dot{V}O_2$ with repeated sprints is accompanied by an accelerated $\dot{V}O_2$ at the onset of each work bout (Figure 2.9). The mechanisms responsible for this effect are poorly understood and have at present only been examined during repeated bouts of submaximal work (Bangsbo *et al.*, 2001; Bohnert *et al.*, 1998; Burnley *et al.*, 2002; Gausche *et al.*, 1989; Gerbino *et al.*, 1996; MacDonald *et al.*, 1997; Rossiter *et al.*, 2001). The consensus of opinion supports a pH-mediated response leading to an increased Bohr shift of the O_2-haemoglobin dissociation curve, increased vasodilation in the working muscles, increased recruitment of motor units, and increased activity of pyruvate dehydrogenase (PDH). However, further investigations are required to fully establish the mechanisms of accelerated $\dot{V}O_2$ kinetics during repeated sprints.

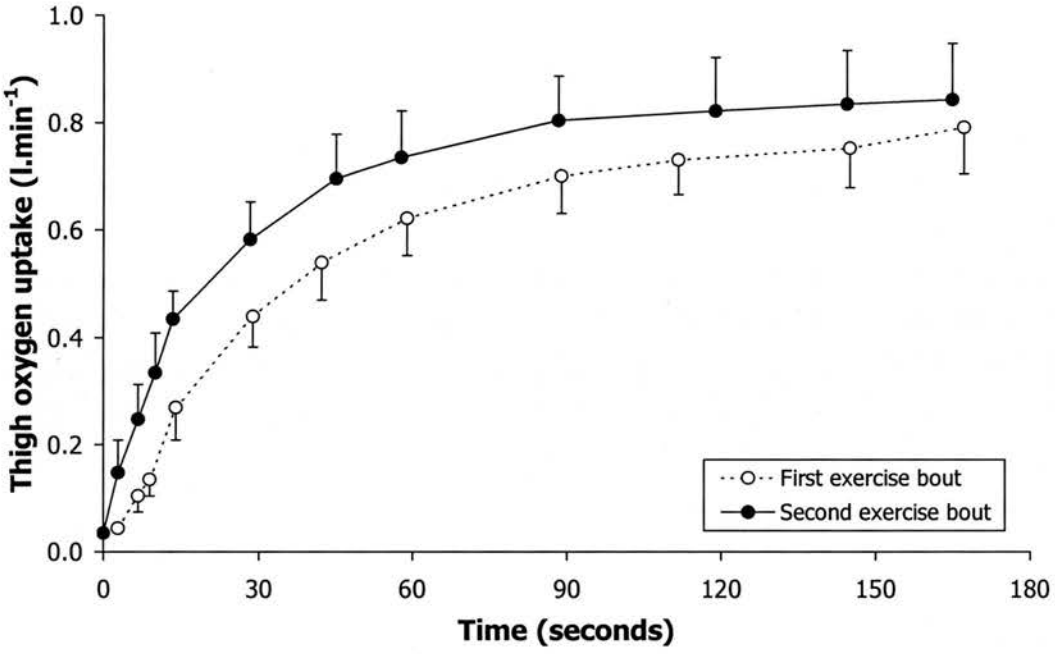


Figure 2.9 Thigh oxygen uptake during 2 x 3-minute bouts of intense (~ 120% $\dot{V}O_{2max}$) knee-extensor exercise separated by a 6-minute period of passive rest. Note: Values are corrected for blood transit times. From: Bangsbo *et al.* (2001).

Although the above investigations support a progressive increase in aerobic ATP production during repeated short maximal sprints, the level of aerobic ATP provision is still considerably less than the overall energy demand (Gaitanos *et al.*, 1993). Moreover, the major role of aerobic metabolism during intermittent short maximal sprints is in its apparently exclusive contribution to the restoration of homeostasis during intervening recovery periods.

2.5 Fatigue during Brief Maximal Intermittent Work

2.5.1 Introduction

Muscular fatigue has been the focus of numerous scientific investigations. At a recent symposium on the subject, McCully *et al.*, (2002) defined fatigue as "the development of less than the expected amount of force as a consequence of muscle activation". During brief maximal intermittent work fatigue is manifested as a progressive decline in power output, the magnitude of which is largely determined by the duration of the intervening recovery periods (Balsom *et al.*, 1992a; Holmyard *et al.*, 1988; Wootton & Williams, 1983) (Figure 2.10). However, during the first few bouts of brief maximal intermittent work, fatigue can

often be masked by a potentiation effect (Figure 2.11). This effect is apparent in a number of investigations (Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988; Robinson *et al.*, 1995; Stone *et al.*, 1999), the mechanisms of which remain largely unresolved (Abbate *et al.*, 2000; Güllich & Schmidtbleicher, 1996; MacIntosh & Rassier, 2002; Smith *et al.*, 2001).

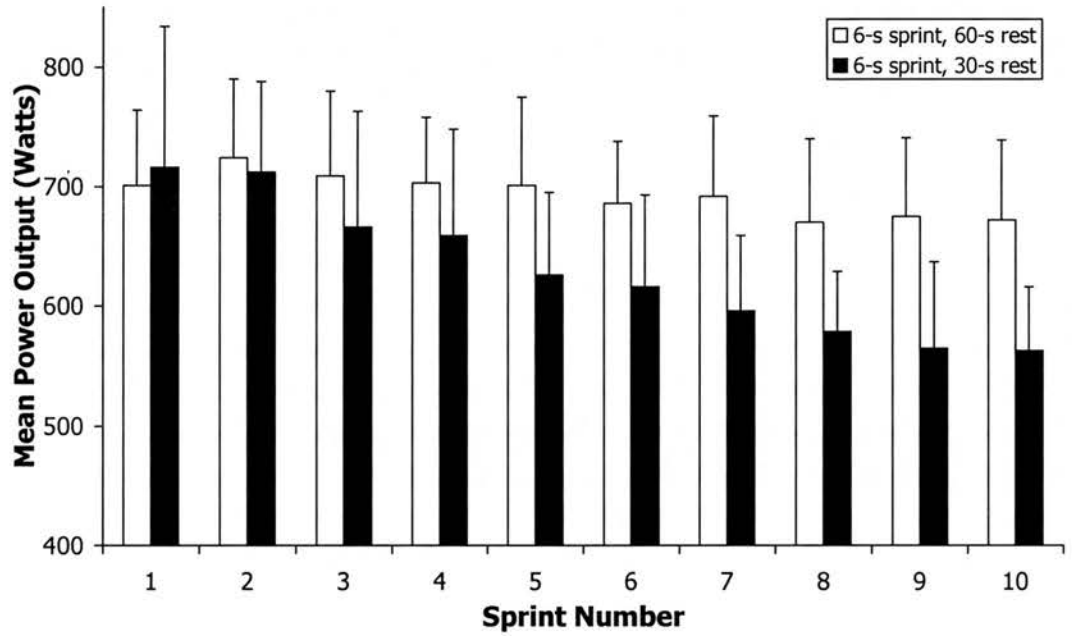


Figure 2.10 Mean power output data during 10 x 6-s maximal treadmill (non-motorised) sprints interspersed with either 30-s or 60-s recovery periods. From: Holmyard *et al.* (1988)

2.5.2 Mechanisms of Fatigue

During repeated bouts of maximal work, fatigue is associated primarily with changes in the intramuscular environment (Bigland-Ritchie & Woods, 1984; Cherry *et al.*, 1998; Duchateau & Hainaut, 1985; MacIntosh & Rassier, 2002). Although the precise aetiology of muscular fatigue remains an issue of much conjecture, causative factors include:

1. A lack of available ATP for actin-myosin coupling, Na^+/K^+ pumping, and Ca^{2+} uptake by the sarcoplasmic reticulum (SR).
2. An inhibition of any of the above by various metabolic by-products.
3. Alterations of excitation-contraction coupling, from the action potential to Ca^{2+} release from the SR (Hultman *et al.*, 1990).

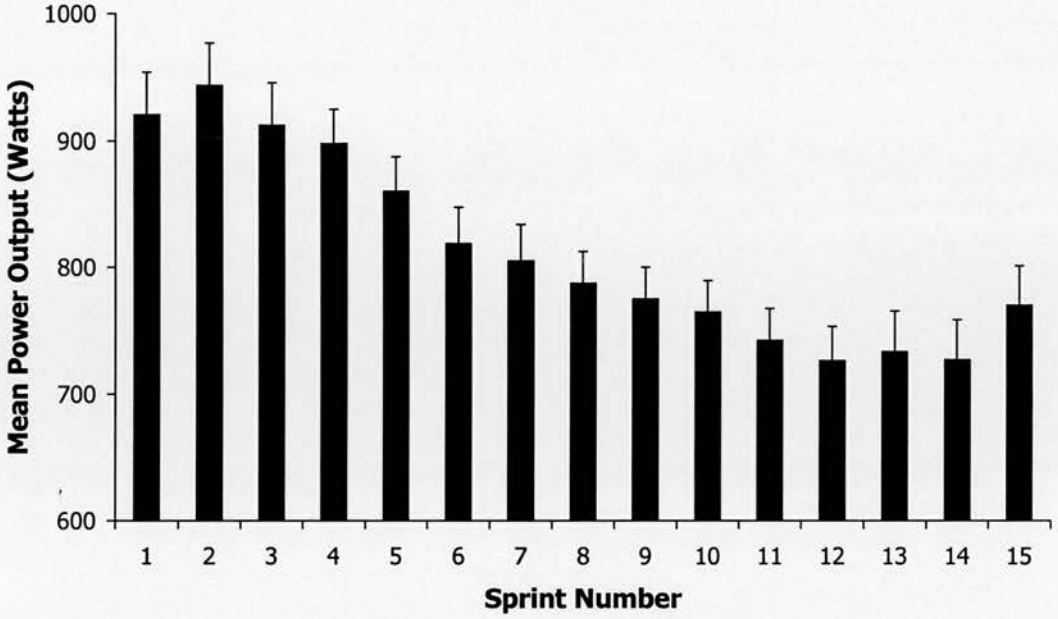


Figure 2.11 Mean power output data during 15 x 5-s bouts of maximal sprint cycling interspersed with 50-s stationary rest periods. From: Robinson *et al.* (1995)

2.5.3 Energy Metabolism and Fatigue

The idea that muscular fatigue may be due to a failure of the metabolic processes to resynthesise ATP at the required rate is supported by the fact that fatigue during repeated bouts of brief maximal work is associated with signs of energy deficiency. i.e. increased concentrations of IMP and hypoxanthine (Balsom *et al.*, 1992a; Balsom *et al.*, 1992b; Hellsten-Westing *et al.*, 1993). Since energy provision during brief maximal sprints is maintained predominantly by anaerobic sources (PCr degradation and glycolysis), deficiencies in energy provision are likely to be associated with limitations in anaerobic metabolism.

2.5.3.1 *PCr availability and fatigue*

Many authors support PCr depletion as the major limiting factor in the development of fatigue during repeated bouts of brief maximal work (Bergström & Hultman, 1991; Bogdanis *et al.*, 1995; Cherry *et al.*, 1998; Hitchcock, 1989; Holmyard *et al.*, 1994; Sahlin & Ren, 1989; Sargeant & Dolan, 1987). This belief is based on the fact that after a bout of intense/maximal work, the recovery of force or power output follows a time-course similar to that of PCr resynthesis (Figure 2.12). The link between PCr availability and fatigue is reinforced by the fact that a number of investigations into repeated sprints have reported

reductions in fatigue following a period of creatine supplementation (Aaserud *et al.*, 1998; Balsom *et al.*, 1993; Greenhaff *et al.*, 1993; Jones *et al.*, 1999; Mujika *et al.*, 2000; Peyrebrune *et al.*, 1998; Yquel *et al.*, 2002) (Figure 2.13). Although there are a number of conflicting reports (Barnett *et al.*, 1996; Cottrell *et al.*, 2002; Dawson *et al.*, 1995; Leenders *et al.*, 1999; McKenna *et al.*, 1999; Schneider *et al.*, 1997; Smart *et al.*, 1998), the above findings suggest that the link between PCr availability and fatigue is likely to be more than just coincidental.

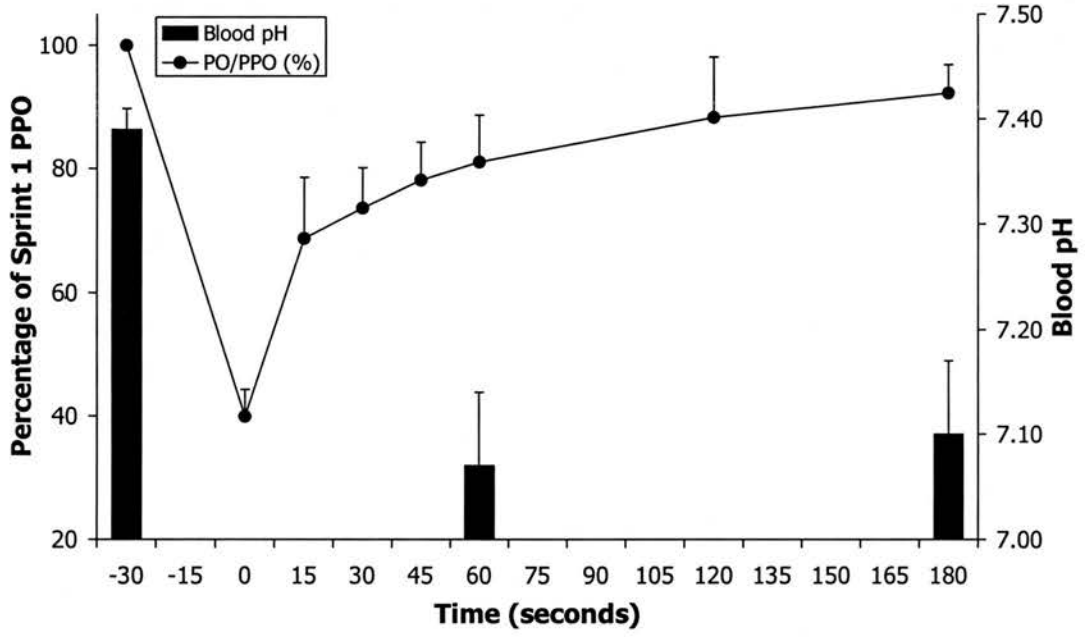


Figure 2.12 Power output (expressed as a percentage of peak power output) and blood pH at rest, and during three minutes of stationary recovery following a 30-s maximal sprint on a non-motorised treadmill. Note: PO = Power output; PPO = Peak power output.

From: Holmyard *et al.* (1994).

2.5.3.2 *Glycogen availability and fatigue*

In contrast to PCr, with a normal resting intramuscular concentration of approximately 300 mmol.kg dm^{-1} (Gaitanos *et al.* 1993; Hultman *et al.*, 1990), glycogen availability is unlikely to be a major limiting factor in the ability to maintain ATP provision during repeated bouts of brief maximal work. This is particularly so given the glycolytic inhibition that appears to accompany this type of work (Bangsbo, 1996; Gaitanos *et al.*, 1993; McCartney *et al.*, 1986; Parolin *et al.*, 1999; Putman *et al.*, 1995; Spriet *et al.*, 1989). However, alterations in glycogen availability via dietary manipulation have been shown to

have a pronounced effect on the ability to maintain high power outputs during the latter stages of repeated bouts of brief high-intensity (> 300% $\dot{V}O_{2max}$) work (Balsom *et al.*, 1999) (Figure 2.14). This effect is particularly evident during prolonged periods of brief high-intensity intermittent work typical of those experienced in many sporting events (Balsom *et al.*, 1999; Nicholas *et al.*, 1995).

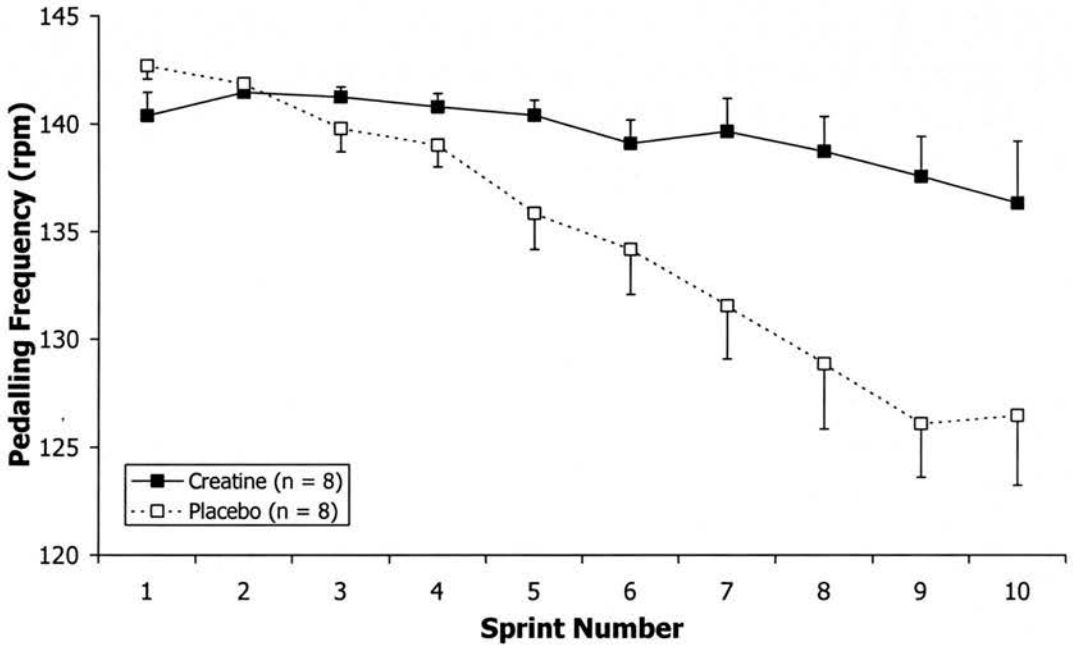


Figure 2.13 Pedalling frequencies during the last two seconds of 10 x 6-s bouts of high-intensity cycling interspersed with 30-s stationary rest periods following a 6-day period of either creatine or placebo administration. Note: Subjects were instructed to try to maintain a pedalling frequency of 140 rpm throughout each sprint. From: Balsom *et al.* (1993).

Although glycogen availability appears to have little influence on the ability to maintain high power outputs during short periods of brief maximal intermittent work, the drop in pH associated with anaerobic glycolysis has often been implicated as a causative agent of muscular fatigue.

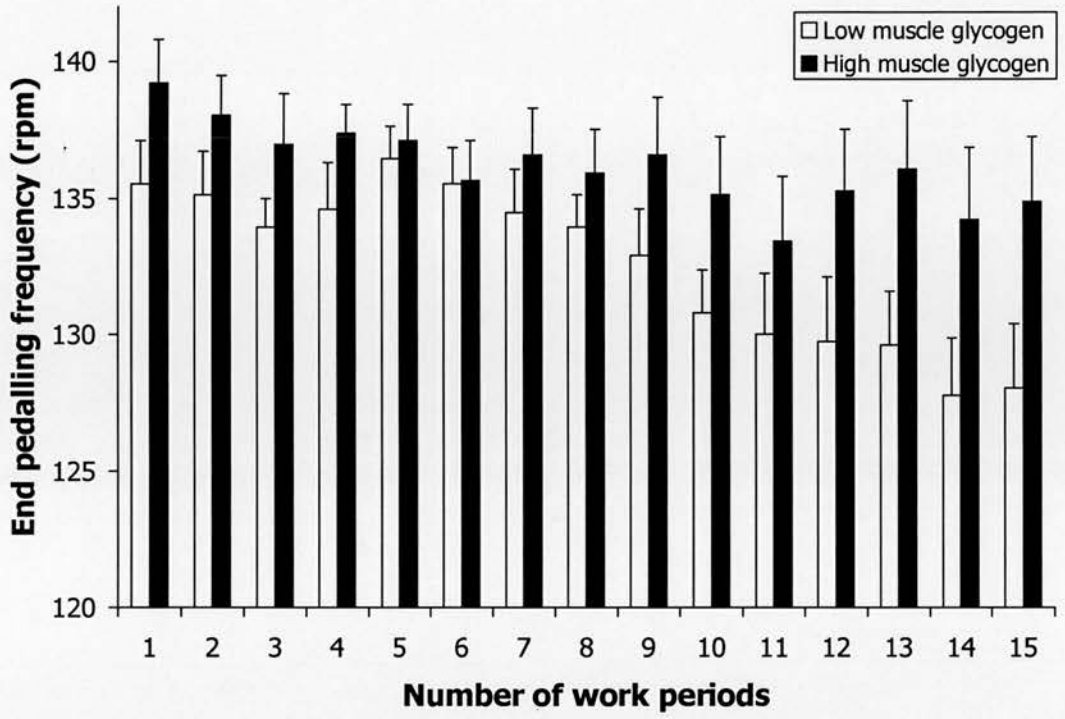


Figure 2.14 The influence of glycogen availability on end pedalling frequency during the last 3-s of 15 x 6-s bouts of high-intensity cycling interspersed with 30-s stationary rest periods. Note: All subjects were instructed to try to maintain a pedal frequency of 140 rpm throughout each work period. From: Balsom *et al.* (1999).

2.5.4 Metabolite accumulation and fatigue

2.5.4.1 *Acidosis and fatigue*

Several studies have shown strong correlations between the decline in intramuscular pH and the reduction in force or power output (Cady *et al.*, 1989; DeGroot *et al.*, 1993; Miller *et al.*, 1988). Moreover, a number of *in vitro* studies on skinned skeletal muscle fibres have reported reductions in isometric force and shortening velocity as a result of acidosis (Chase & Kushmerick, 1988; Cooke *et al.*, 1988; Godt & Nosek, 1989; Kentish & Palmer, 1989; Metzger & Moss, 1987). However, early investigations using skinned fibre preparations were conducted under relatively low temperatures (≤ 15°C) in an attempt to maintain intracellular mechanical stability. In contrast, recent investigations using more advanced techniques report that pH has little effect on contractile function under physiological temperatures (Bruton *et al.*, 1998; Pate *et al.*, 1995; Westerblad *et al.*, 1997; Wiseman *et al.*, 1996). This lack of association between pH and impaired contractile function is reinforced by the fact that the time-course of the recovery of force or power output following a bout of

intense/maximal work is much faster than that of pH (see Figure 2.12). Moreover, high power outputs have been obtained under acidic conditions (Bogdanis *et al.*, 1995; Hitchcock, 1989; Holmyard *et al.*, 1994; Sahlin & Ren, 1989). Although fatigue during brief maximal intermittent work cannot be explained by a direct influence of acidosis on the contractile machinery, acidosis may still impair performance through indirect mechanisms such as its potential role in glycolytic inhibition.

The uncertainty regarding the extent to which acidosis impairs repeat sprint performance is reflected in the results of investigations into the ergogenic effects of sodium bicarbonate ($NaHCO_3$) ingestion. Sodium bicarbonate has been used in a number of studies in an attempt to increase buffering capacity and thereby reduce H^+ accumulation in muscle (Bird *et al.*, 1995; Costill *et al.*, 1984; McNaughton, 1992; Potteiger *et al.*, 1996; Verbitsky *et al.*, 1997; Webster *et al.*, 1993). Using 10 x 10-s sprints (50-s rest periods), Lavender & Bird (1989) reported a significant reduction in fatigue following $NaHCO_3$ administration, the magnitude of which increased with successive sprints (Figure 2.15). In contrast, Gaitanos *et al.*, (1991) reported that $NaHCO_3$ ingestion, despite causing a significant shift in the acid-base balance of the blood, had no effect on repeat sprint (10 x 6-s sprint, 30-s rest) performance. Although the disparity in the results of the two investigations can be reconciled to some extent by the greater glycolytic component of the longer sprints used by Lavender & Bird (1989), further investigations are clearly required to fully establish the precise role, if any, of acidosis in the development of muscular fatigue.

2.5.4.2 *Inorganic phosphate accumulation and fatigue*

Although early research focussed on acidosis as the most likely cause of muscular fatigue, recent findings have led the main focus of attention to switch to that of intracellular inorganic phosphate (P_i) accumulation (Allen *et al.*, 2002; Dahlstedt *et al.*, 2000; Dahlstedt & Westerblad, 2001; Fryer *et al.*, 1995; Kabbara & Allen, 1999). The principle mechanism by which P_i appears to interfere with muscle function is by inhibiting Ca^{2+} release from the SR. Sarcoplasmic reticulum Ca^{2+} release controls actin-myosin cross-bridge interactions and thereby regulates force production. The link between Ca^{2+} release and fatigue has been observed in a number of investigations (Allen *et al.*, 1989; Baker *et al.*, 1993; Gyorke, 1993; Westerblad *et al.*, 1990) and is largely attributed to the calcium-phosphate (Ca^{2+}-P_i) precipitation hypothesis (Allen *et al.*, 2002). In effect, P_i is believed to enter the SR where it

binds to Ca^{2+} to form Ca^{2+}-P_i which in turn leads to a depression of SR Ca^{2+} release (Allen *et al.*, 2002; McLester, 1997; Posterino *et al.*, 2001; Stackhouse *et al.*, 2001; Westerblad *et al.*, 2002). Although SR Ca^{2+}-P_i precipitation is currently considered to be the major cause of muscular fatigue, the mechanism is still largely theoretical and a considerable amount of further research is required to fully establish the mechanisms underlying muscular fatigue. All in all, it appears that muscular fatigue during repeated bouts of brief maximal work is likely to be the result of a spectrum of events rather than a single causative factor, with metabolites such as Na^+ and K^+ also having potential roles to play in its aetiology.

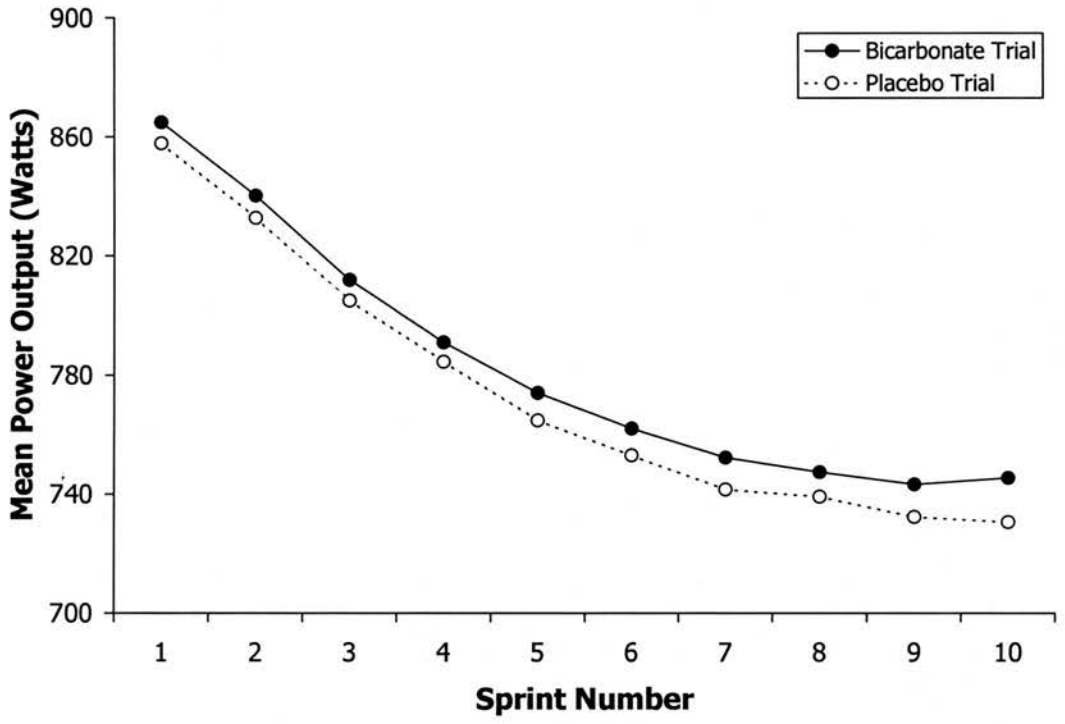


Figure 2.15 The influence of sodium bicarbonate ingestion on mean power output data during 10 x 10-s bouts of maximal sprint cycling interspersed with 50-s stationary rest periods. From: Lavender & Bird (1989)

2.5.5 The Assessment of Fatigue during Brief Maximal Intermittent Work

Despite numerous investigations into the physiological response to repeated bouts of brief maximal work, at present there is no universal way of quantifying the magnitude of fatigue experienced during this type of activity. Several different approaches have been adopted including:

1. The percentage difference in power output/sprint time between the first and last sprints (Brooks *et al.*, 1990).
2. The percentage difference between the maximum and minimum power outputs/sprint times (Hamilton *et al.*, 1991).
3. The back-transformation of the slope of the regression line for log-transformed power output/sprint time data (Paton *et al.*, 2001).
4. The percentage decrement score (Fitzsimons *et al.*, 1993).

However, the reliability and validity of such measures remain largely unresolved. Moreover, the fatigue process during this type of work has primarily been examined over a small (≤ 10) number of sprints and as such, the calculations used may fail to account for the changes that occur in the pattern of fatigue as the number of sprints is extended (see Figure 2.11). Once again, as with the aetiology of muscular fatigue, the quantification of fatigue during repeated bouts of brief maximal work is an area requiring a considerable amount of further investigation.

2.5.6 Summary

This section has shown how performance during repeated bouts of brief maximal work can be influenced by many factors including substrate availability and metabolite accumulation. The final section of this review will examine the influence of another potential performance modulator during repeated bouts of brief maximal work, namely oxygen availability, with particular focus on the influence of endurance training.

2.6 The Influence of Oxygen Availability on Brief Maximal Intermittent Performance

The influence of oxygen availability on performance during both submaximal and maximal workloads has been extensively studied using a wide range of methodologies (Adams & Welch, 1980; Cymerman *et al.*, 1989; Eiken & Tesch, 1984; Frisbee *et al.*, 1999; Fulco *et al.*, 1996; Hogan *et al.*, 1999a; Hogan *et al.*, 1999b; Katz & Sahlin, 1987; Peltonen *et al.*, 1995). In general, hypoxic conditions are associated with increased rates of fatigue, whilst hyperoxic conditions have a contrasting effect. These same effects are also evident in studies that have examined the influence of oxygen availability on repeat sprint performance (Balsom *et al.*, 1994a; Balsom *et al.*, 1994b). For example, under conditions of enhanced oxygen availability (achieved via erythropoietin administration), Balsom *et al.* (1994a)

reported that the ability to maintain performance during 15 x 6-s treadmill sprints (~ 250% $\dot{V}O_{2max}$) interspersed with 24-s rest periods, was associated with a reduced accumulation of anaerobic metabolites (blood lactate and hypoxanthine). In contrast, under hypoxic conditions (hypobaric chamber), the ability to perform 10 x 6-s cycle sprints (~ 350% $\dot{V}O_{2max}$) interspersed with 30-s rest periods, was associated with an increased accumulation of blood lactate, a reduced oxygen uptake, and an increased rate of muscular fatigue (Balsom *et al.*, 1994b) (Figure 2.16). The authors hypothesised that oxygen availability mediated its effect on repeat sprint performance by influencing a) the magnitude of the aerobic contribution to ATP resynthesis during work periods; and/or b) the rate of PCr resynthesis during the intervening rest periods.

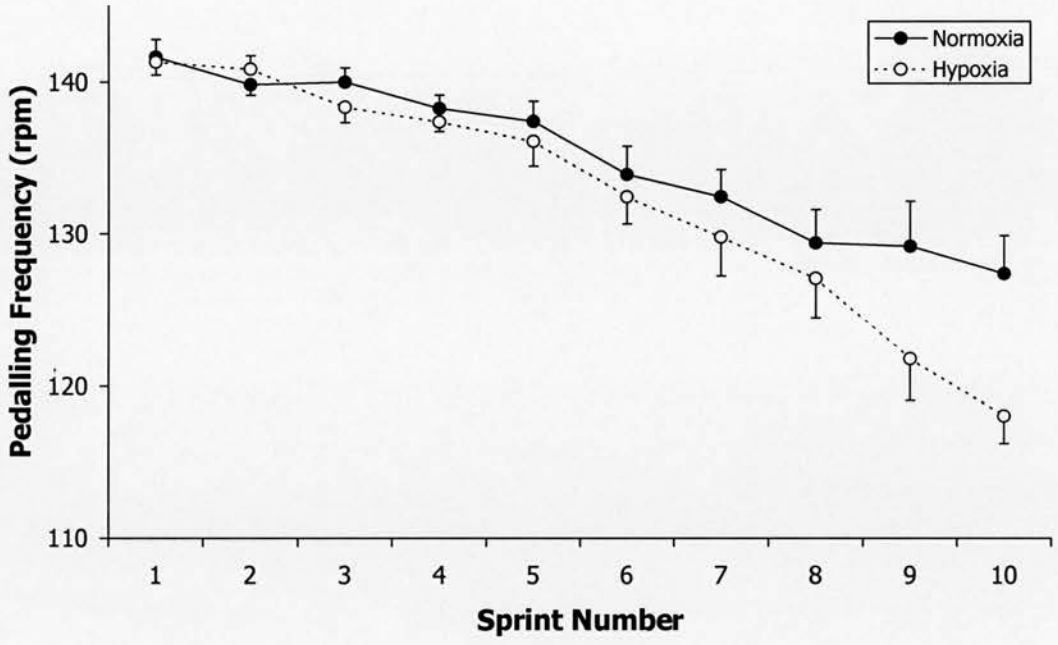


Figure 2.16 Pedalling frequencies during the final second of 10 x 6-s bouts of high-intensity (~ 350% $\dot{V}O_{2max}$) cycling (30-s stationary rest periods) under hypoxic and normoxic conditions. Note: Subjects were instructed to try to maintain a pedalling frequency of 140 rpm throughout each sprint. From: Balsom *et al.* (1994b).

The idea that oxygen availability may have influenced the aerobic contribution to each sprint is supported by evidence from a number of studies that oxygen availability has a significant influence on the rate of oxygen uptake at the onset of high-intensity exercise (Hughson & Kowalchuk, 1995; Linnarsson *et al.*, 1974; MacDonald *et al.*, 1997; Pedersen, 1983).

Specifically, hyperoxic conditions result in a speeding of $\dot{V}O_2$ kinetics at the onset of exercise, whilst hypoxic conditions have the opposite effect. A faster on-transient $\dot{V}O_2$ response, as a result of enhanced oxygen availability, would reduce the magnitude of the oxygen deficit incurred during each sprint and thereby place less demand on anaerobic sources to maintain the required rate of ATP provision.

Although a modified aerobic contribution to ATP resynthesis during each sprint provides a possible explanation for the findings of Balsom *et al.* (1994a & 1994b), the results can also be reconciled by the fact that oxygen availability may have influenced the magnitude of the contribution to ATP resynthesis made by PCr. In effect, the link between oxygen availability and PCr recovery kinetics observed by Haseler *et al.* (1999) and Idström *et al.* (1985) (see Figure 2.2) is likely to have influenced the magnitude of the PCr contribution to ATP turnover during each sprint. A higher PCr availability at the onset of each sprint as a result of hyperoxia would reduce the demand on anaerobic glycolysis to maintain the required rate of ATP turnover.

In addition to the hypotheses put forward by Balsom *et al.* (1994a & 1994b), oxygen availability may have influenced repeat sprint performance via its influence on P_i accumulation. Oxygen availability has been shown to influence the rate of P_i accumulation during exercise (Figure 2.17) and recovery (Hogan *et al.*, 1999b; Idström *et al.*, 1985). As such, the increased rate of fatigue observed by Balsom *et al.* (1994b) under hypoxic conditions may have been the result of a more rapid accumulation of P_i during each sprint, and a reduced rate of removal during recovery.

Although the investigations by Balsom *et al.* (1994a & 1994b) provide a valuable insight into the influence of oxygen availability on repeat sprint performance, the intensities used were less than the maximal intensities often experienced in many sporting activities. Nevertheless, the influence of oxygen availability on repeat sprint performance has led several authors to suggest that aerobic/endurance training may convey an enhanced ability to resist fatigue during this type of work (Aziz *et al.*, 2000; Balsom, 1995; Bell *et al.*, 1997; Bogdanis *et al.*, 1996; Cooke *et al.*, 1997; Dawson *et al.*, 1993; Tomlin & Wenger, 2001). Although the theoretical basis for this assumption is compelling, corroborative scientific evidence is far from substantive.

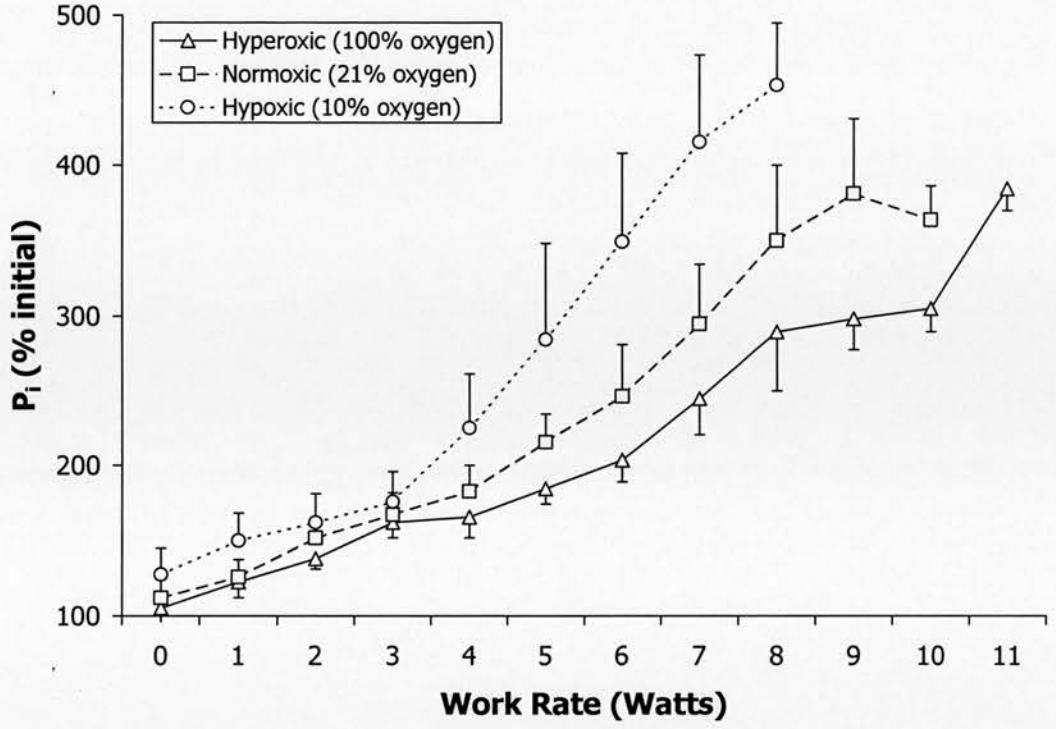


Figure 2.17 The relationship between muscle P_i concentration and work rate for each of three different fractions of inspired oxygen during repeated plantar flexion exercise using ^{31}P-magnetic resonance spectroscopy. From: Hogan *et al.* (1999b)

2.6.1 Endurance training and on-transient oxygen uptake kinetics.

The influence of aerobic (endurance) training on $\dot{V}O_2$ kinetics at the onset of exercise has been the focus of a number of investigations (Carter *et al.*, 2000; Chilibeck *et al.*, 1996; Demarle *et al.*, 2001; Hagberg *et al.*, 1980; Hickson *et al.*, 1978; Norris & Petersen, 1998; Phillips *et al.*, 1995; Yoshida *et al.*, 1992). Although findings are limited by a) a lack of experimentation using maximal workloads; and b) the use of pulmonary gas exchange data to determine the $\dot{V}O_2$ response, the overall consensus of opinion is that aerobic training leads to an elevation in $\dot{V}O_{2max}$ and a speeding of on-transient $\dot{V}O_2$ kinetics.

2.6.2 Endurance training and Phosphocreatine recovery kinetics.

In contrast to the above, information on the influence of aerobic training on PCr recovery kinetics is sparse. However, McCully & Posner (1992) reported enhanced PCr recovery kinetics following two weeks of endurance training. Moreover, a number of investigations have reported enhanced PCr recovery kinetics in endurance-trained athletes in comparison with sprinters and untrained controls (Laurent *et al.*, 1992; McCully *et al.*, 1989; McCully *et*

al., 1992; Takahashi *et al.*, 1995; Yoshida & Watari, 1993). Despite, the considerable amount of evidence supporting a link between endurance training status and PCr recovery kinetics, attempts to establish a relationship between $\dot{V}O_{2max}$ and PCr recovery kinetics show some conflicting results. For example, Cooke *et al.* (1997) reported no significant differences in PCr resynthesis rates between individuals grouped on the basis of whether or not they possessed a high (mean $\dot{V}O_{2max}$: 64.4 ± 1.4 $ml.kg^{-1}.min^{-1}$) or a low (mean $\dot{V}O_{2max}$: 46.6 ± 1.1 $ml.kg^{-1}.min^{-1}$) $\dot{V}O_{2max}$. In contrast, Takahashi *et al.* (1995) reported significant negative correlations between $\dot{V}O_{2max}$ and the time-constants for PCr resynthesis following light, moderate, severe, and exhausting exercise. Moreover, Bogdanis *et al.* (1996) reported that PCr resynthesis rates were strongly correlated ($r = -0.89$; $p < 0.01$) with endurance fitness as determined from the percentage of $\dot{V}O_{2max}$ corresponding to a blood lactate concentration of 4 $mmol.l^{-1}$.

2.6.3 Endurance training and lactate clearance.

One of the ways in which endurance training could potentially enhance repeat sprint performance is by increasing the rate of lactate clearance during intervening rest periods. However, whilst some cross-sectional studies report that endurance-trained athletes possess an enhanced lactate clearance capacity (Freund *et al.*, 1992; Oyono-Enguelle *et al.*, 1990; Taoutaou *et al.*, 1996), others have yielded conflicting results (Bassett *et al.*, 1991; Oosthuyse & Carter, 1999). Methodological differences such as the timing of the lactate samples, and the use of monoexponential rather than biexponential curves to describe lactate recovery data may account for some of these discrepancies. Moreover, in most cases, differences in lactate clearance capacities between endurance-trained and untrained individuals have been assessed during recovery from exercise at the same relative intensity, rather than from the same level of blood lactate accumulation. Although Bassett *et al.* (1991) attempted to address this issue by adjusting individual workloads to produce the same level of blood lactate, subtle differences in peak lactate between the groups may still have compromised the results (Figure 2.18).

In contrast to the number of cross-sectional studies on the influence of endurance training on lactate recovery kinetics, longitudinal investigations on the topic are sparse though nonetheless confusing. For example, Evans & Cureton (1983) reported that 6-weeks of endurance training had no significant effect on the rate of lactate clearance during passive

recovery from exhaustive exercise. In contrast, Fukuba *et al.* (1999) reported that 13 weeks of endurance training improved lactate clearance capacity as determined from the 'slow' rate constant (γ_2) of the biexponential lactate recovery curve. Moreover, Donovan & Pagliassotti (1990) reported that endurance-trained rats achieved higher rates of lactate clearance following exogenous lactate infusion. Although the results of Evans & Cureton (1983) are potentially flawed by the use of monoexponential rather than biexponential curves to describe blood lactate recovery kinetics, the precise influence of endurance training on blood lactate clearance remains equivocal.

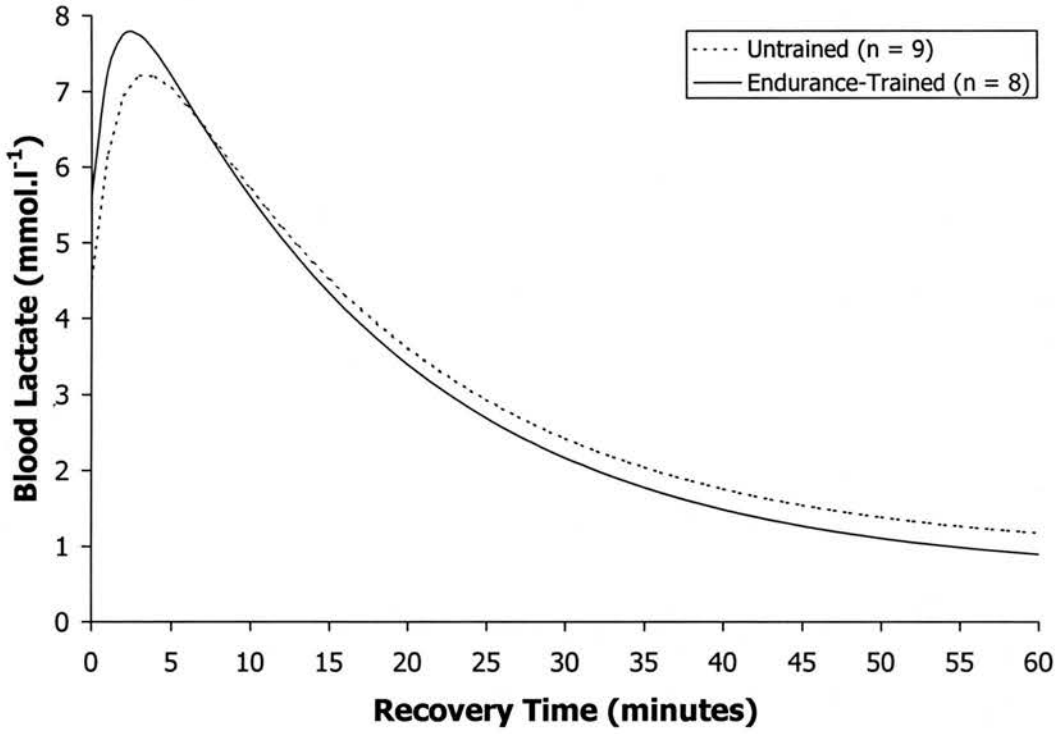


Figure 2.18 Blood lactate in endurance-trained and untrained subjects following three minutes of continuous cycling. From: Bassett *et al.* (1991).

2.6.4 Endurance training and inorganic phosphate kinetics.

A final way in which endurance training could potentially enhance repeat sprint performance is by speeding off-transient P_i kinetics. However, whilst P_i accumulation is currently considered to be the major cause of muscular fatigue, research into the influence of endurance training on P_i accumulation is sparse. In fact, the only study to date that appears to have investigated this topic is a cross-sectional study by Yoshida & Watari (1993) which examined differences between endurance-trained athletes and untrained controls in their

metabolic responses to repeated bouts of work. Although the authors reported no significant differences between the two groups in on-transient P_i kinetics, off-transient Pi kinetics were significantly faster in endurance-trained athletes than in untrained controls (Figure 2.19).

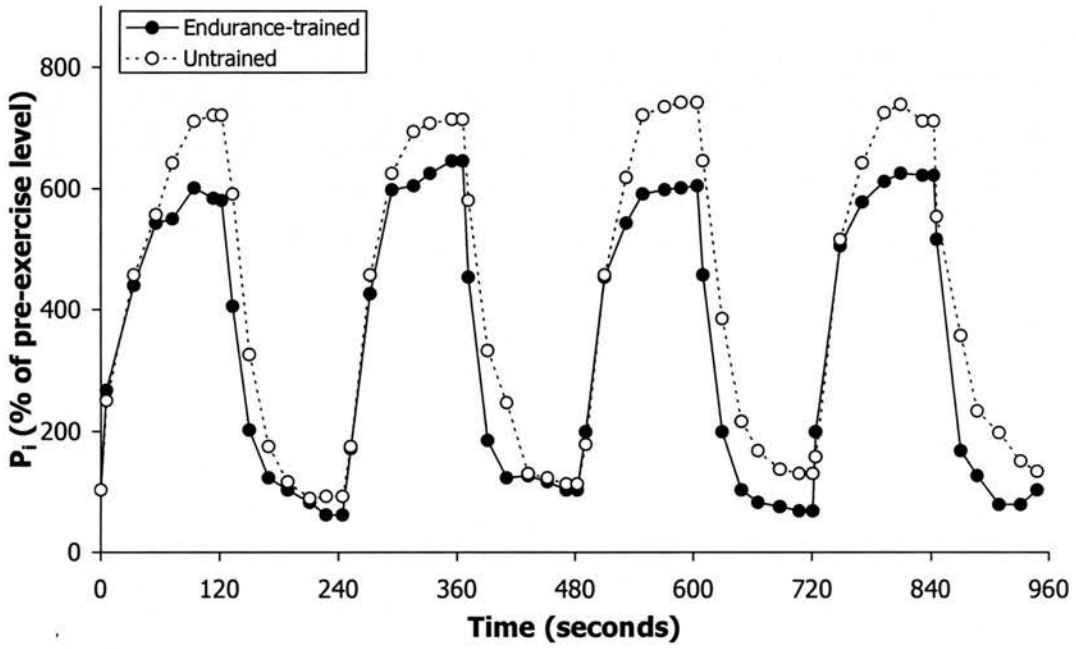


Figure 2.19 Inorganic phosphate kinetics during 4 x 2-minute bouts of repeated knee flexion exercise (20 kgm.min^{-1}) interspersed with 2 minute stationary rest periods in endurance-trained runners and untrained controls. From: Yoshida & Watari (1993)

2.6.5 Endurance training and multiple sprint performance.

Although the results of investigations into the mechanisms by which endurance training may enhance repeat sprint performance are far from conclusive, there is some direct evidence to support the idea that endurance training may enhance performance during this type of work. For example, Hamilton *et al.* (1991) reported that in comparison with games players (mean $\dot{V}O_{2max}$: 52.5 ± 4.9 ml.kg^{-1}.min^{-1}), endurance-trained athletes (mean $\dot{V}O_{2max}$: 60.8 ± 4.1 ml.kg^{-1}.min^{-1}) had an enhanced ability to resist fatigue during 10 x 6-s maximal sprints interspersed with 30-s rest periods (Figure 2.20). Moreover, this enhanced ability to resist fatigue was associated with higher rates of oxygen consumption and lower peak blood lactate concentrations. More recently, Helgerud *et al.* (2001) examined the effects of eight weeks of aerobic interval training on soccer performance. As a result of the training, total match distance increased by 20%, number of sprints increased by 100%, involvement with the ball

increased by 24%, and average work intensity increased from 82.7 ± 3.4% to 85.6 ± 3.1% of maximum heart rate. Although these investigations add further support to the idea that aerobic/endurance training may enhance the ability to perform repeated bouts of brief maximal work, direct evidence of the precise influence of endurance training on repeat sprint performance is lacking. Moreover, attempts to relate various repeat sprint performance indices with one of the key parameters of aerobic fitness, namely $\dot{V}O_{2max}$, reveal conflicting results (Aziz *et al.*, 2000; Bishop *et al.*, 1999; Dawson *et al.*, 1993; Wadley & Le Rossignol, 1998). For example, correlations between relative $\dot{V}O_{2max}$ and fatigue range from r = -0.16 (Aziz *et al.*, 2000) to r = -0.56 (Dawson *et al.*, 1993). Although methodological differences may account for many of the discrepancies, the influence of protocol variation on the magnitude of those discrepancies is at present unknown.

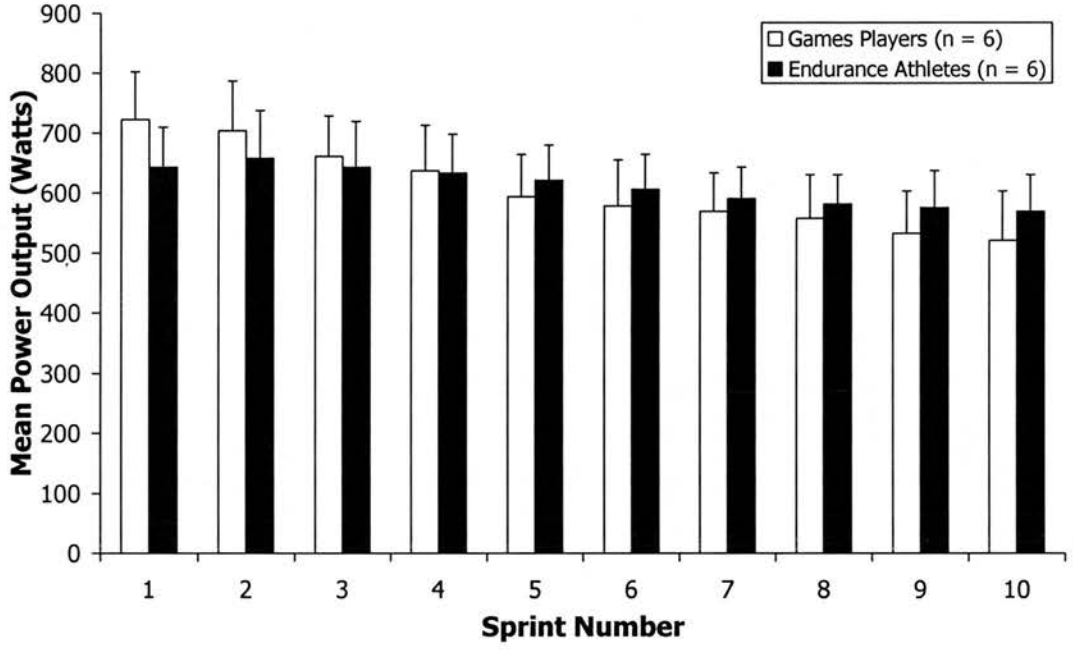


Figure 2.20 Mean power output during 10 x 6-s maximal sprints (non-motorised treadmill) interspersed with 30-s rest periods for a group of games players and a group of endurance-trained runners. Values are means; bars are standard deviations.

From: Hamilton *et al.* (1991)

2.7 Aims

Although this review highlights many unresolved issues regarding the physiological response to repeated bouts of brief maximal work, the principal aim of this thesis was to

focus on one of these issues, namely the influence of aerobic fitness on repeat sprint performance. With this in mind the following series of investigations were conducted:

- Study I investigated the number of familiarisation trials required to establish a high degree of test-retest reliability in measures of power output during two distinct maximal intermittent sprint cycling protocols. The protocols were designed to simulate the range of work to rest ratios often experienced in sports with intermittent activity patterns.

- Study II investigated the reliability and validity of the various methods used to assess fatigue during repeated bouts of brief maximal work.

- Study III examined the influence of recovery duration on various performance measures of brief maximal intermittent work.

- Study IV examined how the physiological variables of $\dot{V}O_{2max}$ and anaerobic capacity correlated with several sport-specific repeat sprint performance indices.

- Study V examined the effects of 6-weeks of endurance training on sport-specific repeat sprint performance.

2.8 Hypotheses

The principal hypotheses of this thesis were that: a) aerobic fitness would have a substantial effect on the ability to maintain performance during repeated bouts of brief maximal work; and b) the magnitude of that effect would be largely determined by the duration of the intervening recovery periods.

3. METHODS

The following section is an overview of the methodologies used in the present thesis. A detailed description of the methodology for each study can be found in the appropriate methods section of each investigation.

3.1 Subjects

Subjects for all the investigations involved in this thesis were recreationally active male physical education and sport science students from the University of Edinburgh. Prior to the commencement of each investigation, subjects were given written instructions concerning the nature of the testing procedures (Appendix A1.1) and written informed consents were obtained (Appendices A1.2, A1.3, and A1.4). In studies III – V, the training status of each subject was assessed through the completion of a training history questionnaire (Appendix A1.5). Ethical approval for each investigation was granted by the University of Edinburgh.

3.2 Equipment

3.2.1 Cycle Ergometer (Studies I – V)

All trials were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was fitted with standard toe-clips and straps and secured to the floor of the laboratory. The flywheel rim of the ergometer was modified by the addition of 90 black-white strips that were interfaced via a photo-reflective opto-sensor with a computer to enable high-frequency logging of the flywheel angular velocity. Flywheel rotations were sampled at a frequency of 18.2 Hz.

3.2.2 Gas Analyser (Studies III – V)

Respiratory gases were analysed using an automated on-line breath-by-breath gas analysis system (Vista Mini CPX; Gold Edition, Vacu-Med, California). The analyser was calibrated before every test using oxygen and carbon dioxide gases of known concentrations (BOC gases, UK) and the flowmeter was calibrated using a 3-litre syringe (Vacu-Med, California). During the tests subjects breathed room air through a facemask (Vacu-Med, California) that was secured in place by a head cap assembly (Hans Rudolph, USA). The gas analyser was interfaced with a computer to provide on-line information (breath-by-breath) on $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory exchange ratio (RER).

3.2.3 Heart Rate Monitors (Studies III – V)

Heart rate data were monitored continuously throughout the tests by means of short-range radio telemetry (Sport-tester, Polar Electro Oy, Finland). The receiver was interfaced with the gas analyser to provide synchronous heart rate and gas exchange data.

3.2.4 Lactate Analyser (Studies III & V)

Blood lactate concentrations were assessed using a hand held Lactate Pro (Arkray: KDK, Japan). The analyser was cleaned and calibrated in accordance with the manufacturers instructions. All blood samples were drawn from a hyperaemised earlobe.

A schematic representation of the equipment set-up for studies III – V, is presented in Figure 3.1.

3.3 Test Protocols

3.3.1 Warm-Up

Each test protocol was preceded by a 5-minute warm-up on the ergometer at 60 revolutions per minute (rpm) against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the tests was determined for each subject before the first test and remained constant for all subsequent tests.

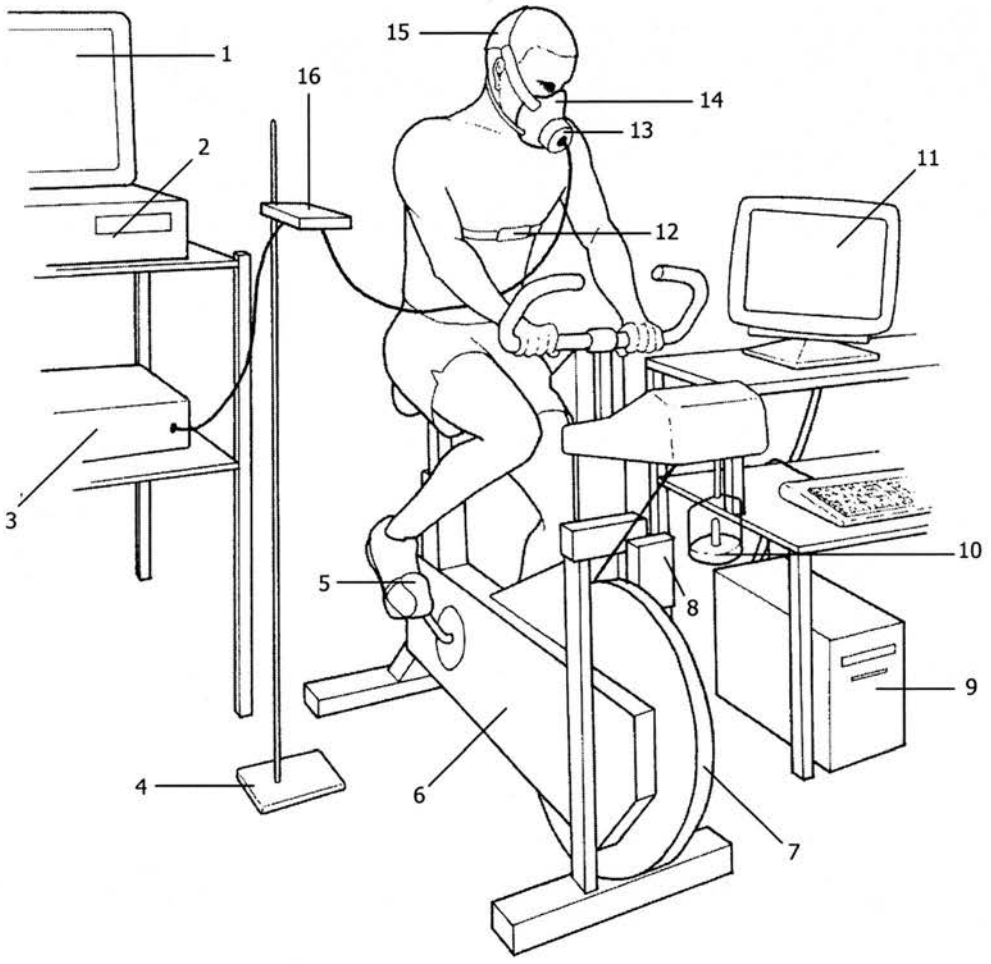
3.3.2 Standardisation

All tests were separated by a minimum 24-hour recovery period, with repeat tests (Studies I, II, & V) conducted at approximately the same time of day. All subjects were instructed to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each test, and to refrain from strenuous exercise in the 24-hour period prior to each test.

3.3.3 Intermittent Tests

Each intermittent test protocol consisted of a series of 20 x 5-s maximal sprints. Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s), the methodology for both intermittent test protocols was the same. Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the test. After a further 3-minute stationary rest period, the test began. Prior to each test

subjects were instructed to remain seated in the saddle for the duration of the test, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort.



1. Monitor.
2. Computer interface for gas analyser.
3. Breath-by-breath gas analyser.
4. Laboratory stand.
5. Toe-clips and straps.
6. Monarch cycle ergometer (Model 814E).
7. Flywheel.
8. Flywheel sensor.
9. Computer interface for cycle ergometer.
10. Flywheel load.
11. Monitor.
12. Heart rate transmitter.
13. Gas turbine.
14. Face mask.
15. Head cap.
16. Heart rate receiver.

Figure 3.1 Schematic illustration of the equipment set-up for studies III – V.

Subjects were given a 5-s countdown before each sprint; the start and finish of which were indicated by a computer-generated audio signal. Subjects were verbally encouraged to give a

maximal effort during every sprint. The flywheel resistance for all tests was set at 0.075 kg.kg body mass^{-1} and the ergometer was calibrated prior to every trial. In studies III, IV, and V, subjects warmed-down by cycling for 5-minutes at 60 rpm against a flywheel resistance of 1.0 kg. A metronome (Seiko, UK) was used to indicate the cadence for this part of the protocol.

Blood lactate measurements were taken immediately before the first sprint, after sprint 10, after sprint 20, and 5-minutes post-test. Individual ratings of perceived exertion (RPE) were monitored during each test (Studies III & V) using a 15-point scale (Borg, 1970). RPE readings were taken after sprints 5, 10, 15, and 20.

Power outputs during each sprint were corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data, measures of peak power output (PP) and mean power output (MP) were calculated for each sprint. Power output data across each intermittent test protocol were derived as measures of maximum PP (PP_{max}), maximum MP (MP_{max}), mean PP (PP_{mean}), and mean MP (MP_{mean}). Fatigue during Studies III, IV, and V was calculated from MP using the performance decrement score devised by Fitzsimons *et al.* (1993):

Performance Decrement Calculation

Fatigue = 100 – ((Total power output ÷ Ideal power output) x 100)

Where:

Total Power Output = sum of MP values from all sprints.

Ideal Power Output = number of sprints x MP_{max}.

A schematic representation of the protocols for the maximal intermittent tests is presented in Figure 3.2.

3.3.4 Maximal Oxygen Uptake (Studies IV & V)

Maximal oxygen uptake was assessed using a modified version of the protocol used by Doherty *et al.* (2000). A metronome and two separate digital readouts were used to help the tester and the subjects ensure that a constant cadence of 80 rpm was observed for all stages

of the test. The test began with three 7-minute exercise bouts of increasing intensity (80W, 120W, and 160W), with five minutes rest between bouts. Immediately after the third bout, the intensity was increased by 40W every two minutes until subjects reached volitional exhaustion. $\dot{V}O_{2max}$ was determined as the highest 20-breath average $\dot{V}O_2$ observed during the test provided that at least two of the following criteria had been met:

- A plateau in $\dot{V}O_2$ at volitional exhaustion.
- An RER value ≥ 1.10
- A maximum heart rate of 220 – age ($\pm$ 10 b.min^{-1})

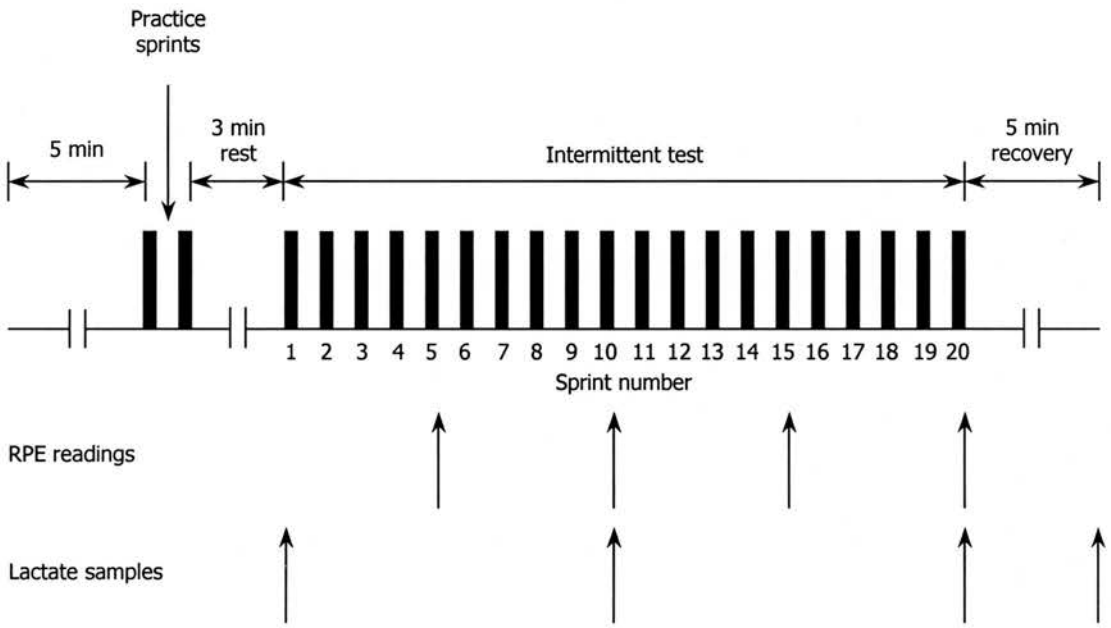


Figure 3.2 Schematic representation of the experimental design for the maximal intermittent test protocols. Note: RPE and blood lactate measures relate to studies III and V only

3.3.5 Maximal Accumulated Oxygen Deficit (Studies IV & V)

Oxygen consumption during the final two minutes of each of the 7-minute submaximal stages of the maximal oxygen uptake test, together with a fixed y-intercept of 5 ml.kg^{-1}.min^{-1} (Medbø *et al.*, 1988) were used to develop linear regression equations of $\dot{V}O_2$ versus power output for each subject. The intensity for the MAOD test (110% of the power output required to elicit $\dot{V}O_{2max}$) was calculated by extrapolation of this regression equation.

After the warm-up subjects were given five minutes of stationary rest before the start of the test. Prior to the test subjects were informed that they should attempt to reach the required cadence of 80 rpm as soon as possible and to maintain this cadence for as long as possible. Two digital readouts and a metronome were used to assist the subjects and the tester. The test was terminated once subjects were no longer able to maintain the required cadence.

Oxygen consumption and heart rate were monitored continuously (breath-by-breath) throughout each test. After allowing 5-s from the start of each test to give subjects time to reach the required cadence, the total oxygen consumption during each test was calculated. Maximal accumulated oxygen deficit (calculated in O_2 equivalents) was determined from the difference between the predicted oxygen demand of the exercise (as determined from the aforementioned regression equation) and the actual oxygen consumption. No adjustment was made in MAOD values for the aerobic component of MAOD (stored oxygen).

3.4 Training Procedures

In Study V, subjects in the experimental group were required to perform continuous training for 20 minutes, three times per week, for six weeks. The intensity for the training sessions (70% of the power output required to elicit $\dot{V}O_{2max}$) was determined from the same regression equations used in the MAOD tests. All training was performed on friction-loaded cycle ergometers (Monark, model 814E). Digital readouts, and music played at a fixed tempo of 160 $b.min^{-1}$ were used to assist the subjects to maintain the required cadence of 80 rpm. Each training session was separated by a minimum 24-hour recovery period. Heart rate data were monitored continuously throughout each training session by means of short-range radio telemetry (Sport-tester: Polar Electro Oy, Finland).

Progressive overload during the training period was applied in a manner similar to that employed by Gaiga & Docherty (1995). At the end of the first week of training the flywheel load was increased by 0.1 kg. This intensity was maintained until the mean heart rate during training returned to the level observed during the first week at which point a further 0.1 kg was added to the flywheel. This process was repeated so that by the end of the training period the mean heart rate response during the final week of training was similar to that recorded during the first week.

3.5 Data Analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Detailed descriptions of the data analysis techniques used in each study are provided in the relevant methods section of each investigation (Chapters 4 to 8).

4. THE RELIABILITY OF POWER OUTPUT DURING SHORT-DURATION MAXIMAL-INTENSITY INTERMITTENT CYCLING

4.1 Introduction

The intermittent sprint protocols used in this thesis were designed to: a) simulate the range of W:R often experienced in many sports with intermittent activity patterns; and b) be of sufficient duration to provide a realistic reflection of sport-specific repeat sprint ability. However, before the tests could be used to assess repeat sprint performance it was important to determine the familiarisation process and the degree of within-subject variation associated with each protocol. Knowledge of the familiarisation process and the degree of within-subject variation associated with any test of human performance is essential for evaluating the effects of various experimental interventions. Despite this observation, research to date on the reliability of tests designed to analyse intermittent performance is limited. Moreover, whilst it may be common practice for researchers to conduct familiarisation trials prior to an investigation to reduce the influence of learning effects on results, information on the influence of familiarisation on test-retest reliability is limited.

4.2 Methods

All subjects completed eight trials of one of the maximal intermittent test protocols to provide sufficient data for familiarisation and reliability analysis. Protocol 1 consisted of twenty 5-s sprints separated by 10-s recovery periods (W:R = 1:2). Protocol 2 consisted of twenty 5-s sprints separated by 30-s recovery periods (W:R = 1:6). All testing was conducted over a three-week period and all trials were separated by a minimum 24-hour recovery period. Subjects were instructed to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each trial, and to refrain from strenuous exercise 24-hours before each trial. Familiarisation was quantified using the statistical procedures outlined by Martin *et al.* (2000). Once the time course of familiarisation had been established, within-subject test-retest reliability was examined over the remaining trials.

4.2.1 Subjects

Two groups of seven recreationally active men volunteered for the investigation. Ethical approval was granted by the University of Edinburgh and all subjects gave their written

informed consent prior to participation. The means ± standard deviation (SD) for age, height, and body mass are presented in Table 4.1.

Table 4.1 Subject characteristics

Protocol	Age (years)	Height (cm)	Body mass (kg)
1	25.0 ± 3.7	176.5 ± 8.1	70.7 ± 3.6
2	25.6 ± 4.1	177.8 ± 6.7	72.5 ± 6.2

4.2.2 Equipment

All trials were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was fitted with standard toe-clips and straps and secured to the floor of the laboratory. The flywheel rim of the ergometer was modified by the addition of 90 black-white strips that were interfaced via a photo-reflective opto-sensor with a computer to enable high-frequency logging of the flywheel angular velocity. The flywheel resistance for all trials was set at 0.075 kg.kg body mass^{-1} and flywheel rotations were sampled at a frequency of 18.2 Hz. The ergometer was calibrated prior to every trial.

4.2.3 Testing Procedures

Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s), the methodology for both intermittent test protocols was the same. Before the start of each trial, subjects completed a 5-minute warm-up at 60 revolutions per minute against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the trials was determined for each subject before the first trial and remained constant for all subsequent trials. Subjects were instructed to remain seated in the saddle for the duration of each trial, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort. Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the trial. After a further 3-minute stationary rest period, the trial began. Subjects were given a 5-s countdown before each sprint, the start and finish of which were indicated by a computer-generated signal. Subjects were verbally encouraged to give a maximal effort during every sprint.

The power output during each sprint was corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data,

the following performance measures were determined for each sprint: peak power output (PP), mean power output (MP), and time to peak power (TPP). Power output data across each intermittent test protocol were derived as measures of maximum PP (PP_{max}), maximum MP (MP_{max}), mean PP (PP_{mean}), mean MP (MP_{mean}), and mean TPP (TPP_{mean}).

4.2.4 Data analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Measures of centrality and spread are presented as means ± SD. The *n* size used in this investigation was determined from a power value of 0.8, an effect size based on previous research (Fitzsimons *et al.*, 1993), and an α level of 0.05. To examine the process of familiarisation, differences in the performance measures of maximum power output (PP_{max} and MP_{max}) were evaluated with a one-way repeated measures analysis of variance (ANOVA). If significant ($p < 0.05$) between-trial differences were observed, a Tukey post-hoc analysis was used to determine where those differences occurred. After determining the number of trials required to limit the effects of familiarisation, measures of within-subject variation (coefficient of variation, CV) were derived from a two-way ANOVA as described by Schabort *et al.* (1999). Power output or TPP_{mean} was the dependent variable in the model, the identity of the subjects was a random effect, and the identity of the trial was a fixed effect. Retest correlations were derived from the ANOVA as intraclass correlation coefficients (ICC) using the method described by Bartko (1966). Confidence limits (95%) for CV and ICC were calculated using the methods outlined by McGraw & Wong (1996) and Tate & Klett (1959).

4.3 Results

4.3.1 Familiarisation

Mean trial scores of PP_{max} are presented in Figure 4.1. Similar trends were observed between values of MP_{max}. Significant between-trial differences in these variables were detected in post-hoc tests involving trials 1 and 2 only.

4.3.2 Reliability

As a result of the above data, reliability was assessed over the last 6 trials of each protocol. Means ± SD of all power data (including TPP) along with CV, ICC and associated 95% confidence limits (CL) are presented in Tables 4.2 – 4.4.

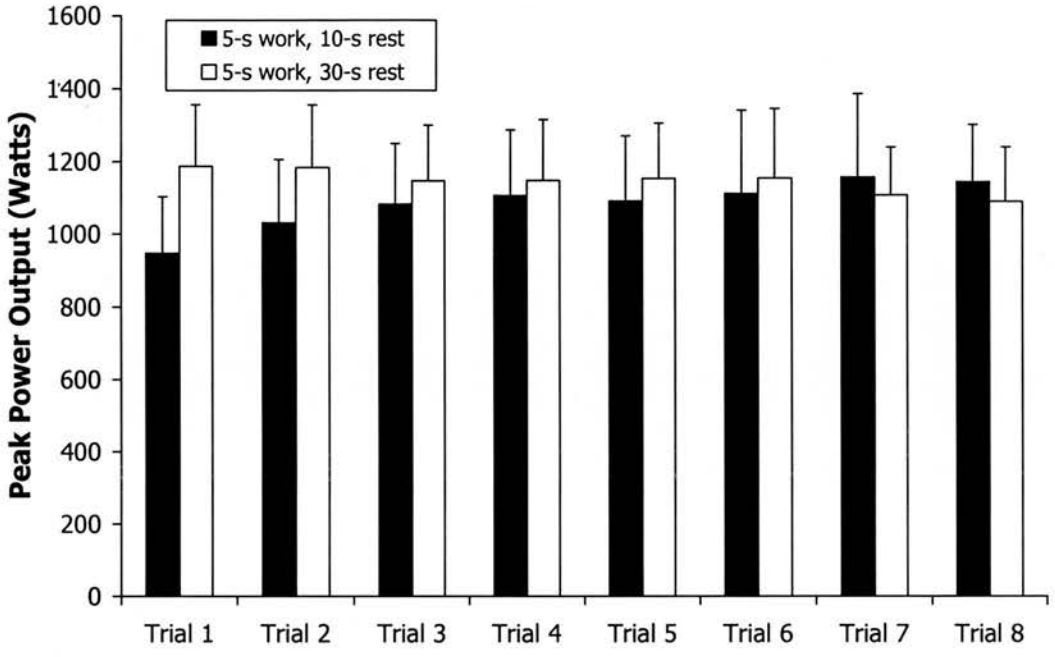


Figure 4.1. Maximum power output data during intermittent sprint cycling trials using different work to rest ratios. Values are means; bars are standard deviations.

Table 4.2 Power output and within-subject test-retest reliability data from intermittent test Protocol 1 (20 x 5-s sprint, 10-s rest).

	Peak Power Data (Watts)		**Mean Power Data (Watts)**	
	Maximum Peak Power	**Mean Peak Power**	**Maximum Mean Power**	**Mean Mean Power**
Means	1114	803	895	644
SD	*183*	*95*	*162*	*85*
CV	8.1	3.3	8.4	3.4
Lower CL	*6.5*	*2.7*	*6.7*	*2.7*
Upper CL	*10.8*	*4.4*	*11.2*	*4.6*
ICC	0.80	0.93	0.83	0.94
Lower CL	*0.57*	*0.81*	*0.62*	*0.83*
Upper CL	*0.96*	*0.98*	*0.96*	*0.99*

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient; CL = 95% Confidence limits.

Table 4.3 Power output and within-subject test-retest reliability data from intermittent test Protocol 2 (20 x 5-s sprint, 30-s rest).

	Peak Power Data (Watts)		Mean Power Data (Watts)	
	Maximum Peak Power	**Mean Peak Power**	**Maximum Mean Power**	**Mean Mean Power**
Means	1132	1033	889	824
SD	*151*	*141*	*116*	*109*
CV	3.7	3.5	2.4	2.6
Lower CL	*3.0*	*2.8*	*1.9*	*2.1*
Upper CL	*5.0*	*4.7*	*3.2*	*3.5*
ICC	0.93	0.94	0.97	0.97
Lower CL	*0.83*	*0.85*	*0.92*	*0.91*
Upper CL	*0.99*	*0.99*	*0.99*	*0.99*

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient; CL = 95% Confidence limits.

Table 4.4 Mean time to peak power data from intermittent test protocols

	Mean Time to Peak Power Data (seconds)	
	Protocol 1	**Protocol 2**
Means	3.59	3.71
SD	*0.40*	*0.39*
CV	8.8	6.4
Lower CL	*7.0*	*5.1*
Upper CL	*11.8*	*8.5*
ICC	0.51	0.63
Lower CL	*0.20*	*0.33*
Upper CL	*0.85*	*0.90*

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient; CL = 95% Confidence limits.

4.4 Discussion

The results of this investigation corroborate the limited number of previous reports suggesting that in subjects unfamiliar with tests of all-out cycling, a minimum of two familiarisation trials are required to establish a high degree of reliability in measures of power output (Capriotti *et al.*, 1999; Martin *et al.*, 2000).

After taking the familiarisation process into account, within-subject variation between trials was assessed across trials 3 – 8. Apart from PP_{max} and MP_{max} in Protocol 1 (Table 4.2), all remaining measures of power output (Tables 4.2 & 4.3) showed high levels of test-retest reliability across both intermittent test protocols. Although the confidence limits allow for the possibility of slight fluctuations in the true magnitude of the data, the results corroborate previous reports of high levels of test-retest reliability in this type of intermittent work (Capriotti *et al.*, 1999; Fitzsimons *et al.*, 1993). Differences between the two intermittent test protocols in terms of within-subject variability in measures of PP_{max} and MP_{max} (Tables 4.2 & 4.3) are difficult to elucidate. Although subject motivation was a possible confounding factor, increases in the mean values of PP_{max} (see Figure 4.1) and MP_{max} during the first three trials of Protocol 1 suggests that a lack of subject motivation was not a cause for concern.

Research into the reliability of power output data during single bouts of maximal sprint cycling (≤ 30-s) suggests that the reliability of mean power output data is superior to peak power output data (Hopkins *et al.*, 2001). Although the reliability of mean power output relative to peak power output was similar in Protocol 1 (Table 4.2), overall the results of this investigation suggest that greater precision in single trials, and more effective monitoring of changes between trials, can best be achieved through the use of mean power output data.

Although the reliability of TPP has previously been examined during single bouts of maximal sprint cycling (≤ 30-s) (Nicklin, *et al.*, 1990; Williams *et al.*, 1988), this investigation appears to be the first to examine test-retest reliability in measures of TPP during intermittent work. Despite the moderate degrees of test-retest reliability shown (Table 4.4), the confidence limits allow for the fact that the true magnitude of the degree of reliability could be anything from poor to good. Further research with a larger sample size would improve the accuracy of these estimates.

4.5 Conclusions

Tests of repeat sprint ability are becoming increasingly commonplace as a means of evaluating the effects of various experimental interventions on the performance capabilities of team sport players. The results of this investigation suggest that in subjects unfamiliar with such tests, a minimum of two practice trials are required to reduce the associated

learning effects. Once familiarisation has been established, most measures of repeat sprint performance can be assessed with a high degree of test-retest reliability.

5. THE RELIABILITY AND VALIDITY OF FATIGUE MEASURES DURING SHORT-DURATION MAXIMAL-INTENSITY INTERMITTENT CYCLING.

5.1 Introduction

After establishing the reliability of the two intermittent test protocols to be used for this thesis, the second task was to establish the most valid and reliable means of assessing fatigue during this type of work. Muscular fatigue is one of the main factors limiting performance during the prolonged periods of play experienced in multiple sprint sports. However, despite numerous investigations into the physiological response to this type of work, there is no universal way of assessing this parameter. The aim of the second investigation of this thesis was to address this issue by examining the reliability and validity of the various approaches used to quantify fatigue during brief maximal intermittent work. Four formulae were examined and in each case fatigue was calculated from MP data:

5.2 Methods

Following the completion of two familiarisation trials as established in Study I and as recommended by Capriotti *et al.* (1999), all subjects completed six trials of one of the maximal intermittent test protocols over a three-week period. All trials were separated by a minimum 24-hour recovery period. Protocol 1 consisted of twenty 5-s sprints separated by 10-s recovery periods (W:R = 1:2). Protocol 2 consisted of twenty 5-s sprints separated by 30-s recovery periods (W:R = 1:6). Subjects were asked to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each trial, and to refrain from strenuous exercise 24-hours before each trial.

5.2.1 Subjects

Two groups of seven recreationally active male subjects volunteered for the study. Ethical approval was granted by the University of Edinburgh and all subjects gave their written informed consent prior to participation. The means ± standard deviation (SD) for age, height, and body mass are presented in Table 5.1.

Table 5.1 Subject characteristics

Protocol	Age (years)	Height (cm)	Body mass (kg)
1	25.0 ± 3.7	176.5 ± 8.1	70.7 ± 3.6
2	25.6 ± 4.1	177.8 ± 6.7	72.5 ± 6.2

5.2.2 Equipment

All trials were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was interfaced with a computer to enable high-frequency logging of the flywheel angular velocity. The ergometer was fitted with standard toe-clips and straps and secured to the floor of the laboratory. The flywheel resistance for all trials was set at 0.075 kg.kg body mass^{-1} and flywheel rotations were sampled at a frequency of 18.2 Hz. The ergometer was calibrated prior to every trial.

5.2.3 Testing Procedures

Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s), the methodology for both intermittent test protocols was the same. Before the start of each trial, subjects completed a 5-minute warm-up at 60 revolutions per minute against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the trials was determined for each subject before the first trial and remained constant for all subsequent trials. Subjects were instructed to remain seated in the saddle for the duration of each trial, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort. Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the trial. After a further 3-minute stationary rest period, the trial began. Subjects were given a 5-s countdown before each sprint the start and finish of which were indicated by a computer-generated audio signal. Subjects were verbally encouraged to give a maximal effort during every sprint.

The power output during each sprint was corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data values of mean power output (MP) were calculated for each sprint. Fatigue during each trial was calculated from MP using the following formulae:

Formula 1 (F1).

Fatigue = the percentage difference in MP between the first and last sprints (Brooks *et al.*, 1990).

Calculation:

Fatigue = $((MP_{sprint\ 1} - MP_{sprint\ 20}) \div MP_{sprint\ 1}) \times 100$

Formula 2 (F2).

Fatigue = the percentage difference between the maximum and minimum values of MP (Hamilton *et al.*, 1991).

Calculation:

Fatigue = $((MP_{max} - MP_{min}) \div MP_{max}) \times 100$

Formula 3 (F3).

Fatigue = the back-transformation of the slope of the line of best fit for log-transformed MP values over all 20 sprints (Paton *et al.*, 2001).

Calculation:

Fatigue = $(100 \times EXP^{(Slope \div 100)}) - 100$

Where:

Slope = (the slope of the line of best fit for: 100 x natural logarithm of MP data) x (number of sprints – 1).

Formula 4 (F4).

Fatigue = the percentage decrement score (Fitzsimons *et al.*, 1993).

Calculation:

Fatigue = 100 – ((Total power output ÷ Ideal power output) x 100)

Where:

Total Power Output = sum of MP values from all sprints.

Ideal Power Output = number of sprints x MP_{max}.

5.2.4 Data Analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Measures of centrality and spread were derived from the average of the mean values for each subject over the six trials, and are presented as means and standard deviations. In the case of F3, Pearson correlation coefficients were used to assess the relationship between the log-transformed power output data and sprint number for each subject. Measures of within-subject variation (typical error, TE) were derived from a two-way analysis of variance (ANOVA). Fatigue was the dependant variable in each model, the identity of the subjects was a random effect, and the identity of the trial was a fixed effect. Retest correlations were derived from the ANOVA as intraclass correlation coefficients (ICC) using the method described by Bartko (1966). Confidence limits (95%) for TE and ICC were calculated using the methods outlined by McGraw & Wong (1996) and Tate & Klett (1959). All fatigue calculations that resulted in negative values were treated as zero fatigue scores.

5.3 Results

Mean values of MP for each sprint across all trials, in both intermittent test protocols, are presented in Figure 5.1. Results of the fatigue scores for both intermittent test protocols are presented in Table 5.2. In the case of F3, correlation coefficients between the log-transformed power output data and sprint number produced mean values of -0.73 ± 0.25 and -0.22 ± 0.41 in Protocols 1 and 2 respectively. Zero fatigue scores were derived only from formulas F1 and F3 and occurred predominantly in Protocol 2. In total, there were 12 incidences of zero fatigue from F1, and 20 from F3.

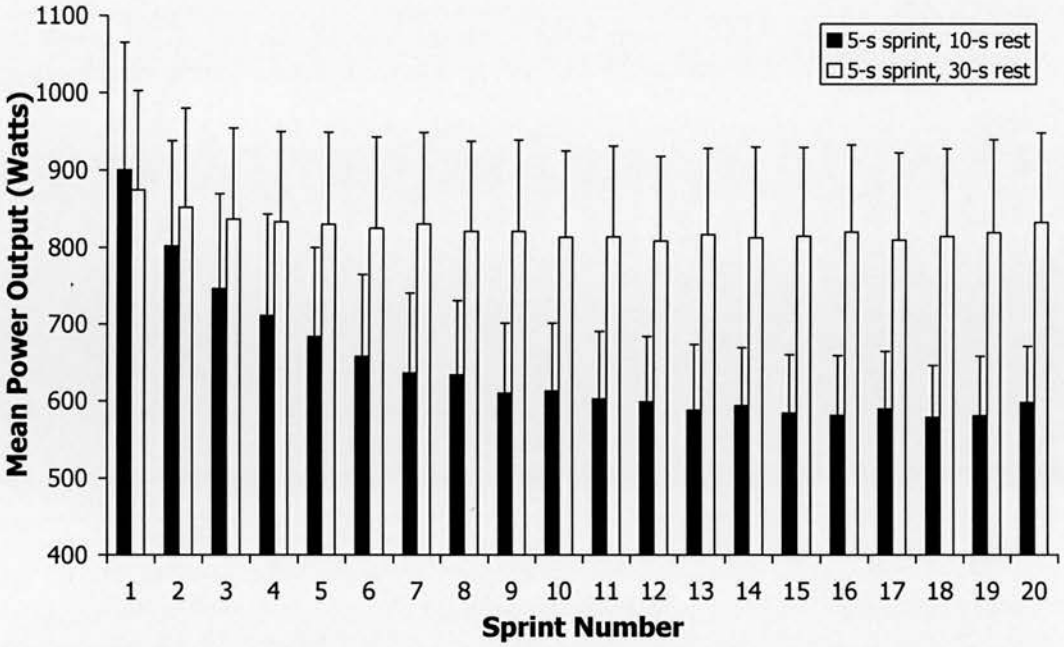


Figure 5.1 Power output data during brief maximal intermittent sprint cycling trials using different work to rest ratios. Values are means; bars are standard deviations.

Table 5.2. Fatigue scores and within-subject test-retest reliability data as calculated from four separate formulae during brief maximal intermittent sprint cycling trials using different work to rest ratios.

	Fatigue Scores – Protocol 1				**Fatigue Scores – Protocol 2**			
Formulae	**1**	**2**	**3**	**4**	1	**2**	**3**	**4**
Means (%)	31.73	37.99	40.64	27.30	5.43	13.36	5.18	7.42
SD	*12.54*	*11.66*	*23.32*	*9.65*	*4.88*	*5.68*	*7.48*	*4.57*
Typical Error	6.64	4.94	9.35	4.60	3.71	2.69	3.53	2.02
Lower CL	*5.31*	*3.95*	*7.47*	*3.68*	*2.96*	*2.15*	*2.82*	*1.61*
Upper CL	*8.88*	*6.60*	*12.50*	*6.15*	*4.96*	*3.60*	*4.72*	*2.70*
ICC	0.77	0.84	0.86	0.81	0.61	0.81	0.78	0.83
Lower CL	*0.52*	*0.64*	*0.66*	*0.58*	*0.30*	*0.58*	*0.54*	*0.62*
Upper CL	*0.95*	*0.97*	*0.97*	*0.96*	*0.90*	*0.96*	*0.95*	*0.96*

Note: ICC = Intraclass correlation coefficient; CL = 95% Confidence limits

5.4 Discussion

Fatigue can be simply defined as the development of less than the expected amount of force as a consequence of muscle activation (McCully *et al.*, 2002), the mechanisms of which are usually specific to the type of work involved. During brief maximal intermittent work,

fatigue is usually evident as a progressive decline in power output, the magnitude of which is largely determined by the duration of the intervening rest periods (Balsom *et al.*, 1992a; Holmyard *et al.*, 1988; Wootton & Williams, 1983) (see Figure 5.1). However, the fatigue process during repeated bouts of brief maximal work has previously only been examined over a small ($\leq$ 10) number of sprints (Fitzsimons *et al.*, 1993; Gaitanos *et al.*, 1993; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988; Paton *et al.*, 2001; Wootton & Williams, 1983). As such, the calculations devised to assess fatigue may fail to consider the changes that occur in the pattern of fatigue as the number of sprints is extended (Nagahama *et al.*, 1993; Robinson *et al.*, 1995; Stone *et al.*, 1999).

Apart from the results derived from F1, the large ICC values of this investigation (Table 5.2) support the reasonably good level of test-retest reliability previously reported for this type of intermittent work (Fitzsimons *et al.*, 1993; Paton *et al.*, 2001). Despite this observation, the confidence limits allow for the possibility that the true magnitude of the ICC values for measures of fatigue determined from formulas F2, F3, and F4 could be anything from large to almost perfect. Further research with a larger sample size would provide more precise estimations of the true magnitude of the scores.

The main reason for assessing the test-retest reliability of a measure such as fatigue is to determine the degree of within-subject variation in the measure. High degrees of reliability improve the precision of single measurements and enhance the ability to monitor changes in performance as a result of experimental interventions. Although formulas F2, F3, and F4 show a reasonably good level of test-retest reliability, the magnitude of the TE's in relation to the mean fatigue scores suggests that it would be difficult to detect any true changes in fatigue from calculations other than those of F2 and F4.

Despite the lack of an established 'gold standard' with which to validate the results, between-protocol differences in the magnitude of the fatigue scores suggests that all formulae were assessing a similar construct. However, within-protocol differences in the magnitude of the fatigue scores highlights a number of limitations. Calculating fatigue from the percentage difference in power output between the first and last sprints (F1) has been used in a number of investigations (Brooks *et al.*, 1990; Gaitanos *et al.*, 1993; Holmyard *et al.*, 1988; Wootton & Williams, 1983). The main limitation of this approach is that the

highest and lowest power output values do not always occur at these extremes (Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988). Formula 2 attempts to account for this effect by using maximum and minimum values of power output (Hamilton *et al.*, 1991), however this technique still fails to consider the fatigue process over an entire trial. Although, F3 and F4 calculate fatigue using power output data from every sprint, these protocols also have certain limitations. In the case of F3, the substantially lower fatigue scores obtained from this formula compared with formulas 1, 2, and 4, support several potential problems. Firstly, the calculation assumes a linear relationship between sprint number and log-transformed power output data. Although Paton *et al.* (2001) reported that the technique worked well with 10 x 20 m sprints repeated every 10 seconds, the correlation coefficients observed in this investigation, particularly in Protocol 2, show that this is not always the case. Secondly, the fatigue patterns observed in both protocols support a minimal amount of fatigue in the second half of each trial. Therefore, for any measure of fatigue to be valid, it should produce similar fatigue scores for the whole trial as for the first half of each trial. In contrast, F3 would result in progressively lower fatigue scores as the number of sprints increased. Finally, although the fatigue pattern observed in Protocol 2 supports a minimal amount of fatigue, the large number of zero fatigue scores obtained from both F3 and F1 suggests inadequacies in both formulae.

Of all the formulae used to assess fatigue in this investigation, F4 has arguably undergone the greatest scrutiny. The formula was developed as a result of a series of studies on sport-specific intermittent work (Dawson *et al.*, 1984; Dawson *et al.*, 1991; Fitzsimons *et al.*, 1993) and has been used in a number of investigations (Aziz *et al.*, 2000; Dawson *et al.*, 1993; Dawson *et al.*, 1998; Wadley & Le Rossignol, 1998). The main limitation of this approach is the presumption that maximum power output occurs in the first sprint. Although this premise may be true for test protocols that result in high levels of fatigue (i.e. Paton *et al.*, 2001), the same may not be true for test protocols in which only a small amount of fatigue is observed (i.e. Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988).

5.5 Conclusions

Intermittent sprint tests are becoming increasingly commonplace as a means of evaluating the performance capabilities of athletes involved in multiple sprint sports. One of the main factors limiting performance during this type of work is the development of fatigue.

Although several different approaches have been taken to quantify this parameter, in comparison with other formulae the results of this investigation support the use of the percentage decrement score (F4) as the most valid and reliable means of assessing fatigue during brief maximal intermittent work.

6. THE INFLUENCE OF RECOVERY DURATION ON BRIEF MAXIMAL INTERMITTENT CYCLING PERFORMANCE

6.1 Introduction

The main purpose of the third investigation of this thesis was to examine the influence of recovery duration on repeated bouts of brief maximal work. Previous research in this area had focused on recovery periods greater than or equal to 30-s (Balsom *et al.*, 1992a; Holmyard *et al.*, 1988; Wootton & Williams, 1983). However, in many multiple sprint sports, recovery periods may at times last little more than a few seconds. Indeed in sports such as badminton and squash, mean recovery periods as short as 10-s are commonplace (Majumdar *et al.*, 1997; Montpetit, 1990).

6.2 Methods

6.2.1 Subject Group

Twenty-five male physical education and sport science students from the University of Edinburgh volunteered to participate in the study. The means ± standard deviation (SD) for age, height, body mass, and predicted percentage body fat (Jackson & Pollock, 1978) were: 20.6 ± 1.5 years, 177.2 ± 5.4 cm, 78.2 ± 8.2 kg, and 11.9 ± 4.7% respectively. Ethical approval for the study was granted by the University of Edinburgh and all subjects gave their written informed consent prior to participation. Prior to commencement all subjects completed a training history questionnaire (Appendix A1.5), which indicated that all were recreational athletes who had been actively involved in sport for an average of approximately thirteen years.

6.2.2 Research Design

Each subject completed two intermittent test protocols with contrasting recovery periods and each protocol was separated by a minimum 24-hour rest period. Protocol 1 consisted of twenty 5-s sprints separated by 10-s recovery periods. Protocol 2 consisted of twenty 5-s sprints separated by 30-s recovery periods. Subjects were asked to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each test, and to refrain from strenuous exercise 24-hours before each test.

6.2.3 Equipment

All test protocols were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was interfaced with a computer to enable high-frequency logging of the flywheel angular velocity. The ergometer was fitted with standard toe-clips and straps and secured to the floor of the laboratory. Each test protocol was preceded by a 5-minute warm-up on the ergometer at 60 revolutions per minute (rpm) against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the tests was determined for each subject before the first test and remained constant for both tests.

Respiratory gases were analysed using an automated on-line breath-by-breath gas analysis system (Vista Mini CPX; Gold Edition, Vacu-Med, California). The analyser was calibrated before every test using oxygen and carbon dioxide gases of known concentrations (BOC gases, UK) and the flowmeter was calibrated using a 3-litre syringe (Vacu-Med, California). During the tests subjects breathed room air through a facemask (Vacu-Med, California) that was secured in place by a head cap assembly (Hans Rudolph, USA). Heart rate data were monitored continuously throughout the tests by means of short-range radio telemetry (Sport-tester, Polar Electro Oy, Finland). The gas analyser was interfaced with a computer that provided on-line information (breath-by-breath) on $\dot{V}O_2$, $\dot{V}CO_2$, respiratory exchange ratio (RER), and heart rate.

Blood lactate concentrations were assessed using a hand held Lactate Pro (Arkray: KDK, Japan). The reliability ($r = 0.99$) and validity of this equipment has previously been reported (Pyne *et al.*, 2000). The analyser was cleaned and calibrated in accordance with the manufacturers instructions. All blood samples were drawn from a hyperaemised earlobe.

6.2.4 Test Protocols

Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s) the methodology for both of the intermittent test protocols was the same. The flywheel resistance for all tests was set at 0.075 kg.kg body mass^{-1} and flywheel rotations were sampled at a frequency of 18.2 Hz. In accordance with the results of Study I and the recommendations made by Capriotti *et al.* (1999), all subjects completed 2 familiarisation trials of both intermittent test protocols prior to commencement of the study.

Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the test. After a further 3-minute stationary rest period, the test began. Prior to each test subjects were instructed to remain seated in the saddle for the duration of the test, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort.

Subjects were given a 5-s countdown before each sprint; the start and finish of which were indicated by a computer-generated audio signal. Subjects were verbally encouraged to give a maximal effort during every sprint. After the final sprint, subjects cycled at 60 rpm for 5-minutes against a flywheel resistance of 1.0 kg. A metronome (Seiko, UK) was used to indicate the cadence for this part of the test.

Blood lactate measurements were taken immediately before the first sprint, after sprint 10, after sprint 20, and 5-minutes post-test. Individual ratings of perceived exertion (RPE) were monitored during each test using a 15-point scale (Borg, 1970). RPE readings were taken after sprints 5, 10, 15, and 20.

Power outputs during each sprint were corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data, measures of peak power output (PP) and mean power output (MP) were calculated for each sprint. Power output data across each intermittent test protocol were derived as measures of maximum PP (PP_{max}), maximum MP (MP_{max}), mean PP (PP_{mean}), and mean MP (MP_{mean}). In accordance with the results of Study II, fatigue during each test was calculated from MP using the performance decrement score devised by Fitzsimons *et al.* (1993):

Performance Decrement Calculation

Fatigue = 100 – ((Total power output ÷ Ideal power output) x 100)

Where:

Total Power Output = sum of MP values from all sprints.

Ideal Power Output = number of sprints x MP_{max}.

6.2.5 Data Analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Measures of centrality and spread are presented as means ± SD. Differences between the two intermittent test protocols, in terms of the various performance measures, were evaluated using paired t-tests. The same analyses provided 95% confidence limits for all measures.

6.3 Results

6.3.1 Power Output

Mean power output data from the intermittent test protocols are illustrated in Figure 6.1, with a summary of all power output data presented in Table 6.1. There were no substantial differences between the two test protocols in measures of power output recorded during sprint 1. However, whilst 92% of maximum power output values (PP_{max} and MP_{max}) during Protocol 1 occurred in sprint 1, the corresponding value for Protocol 2 was only 24%.

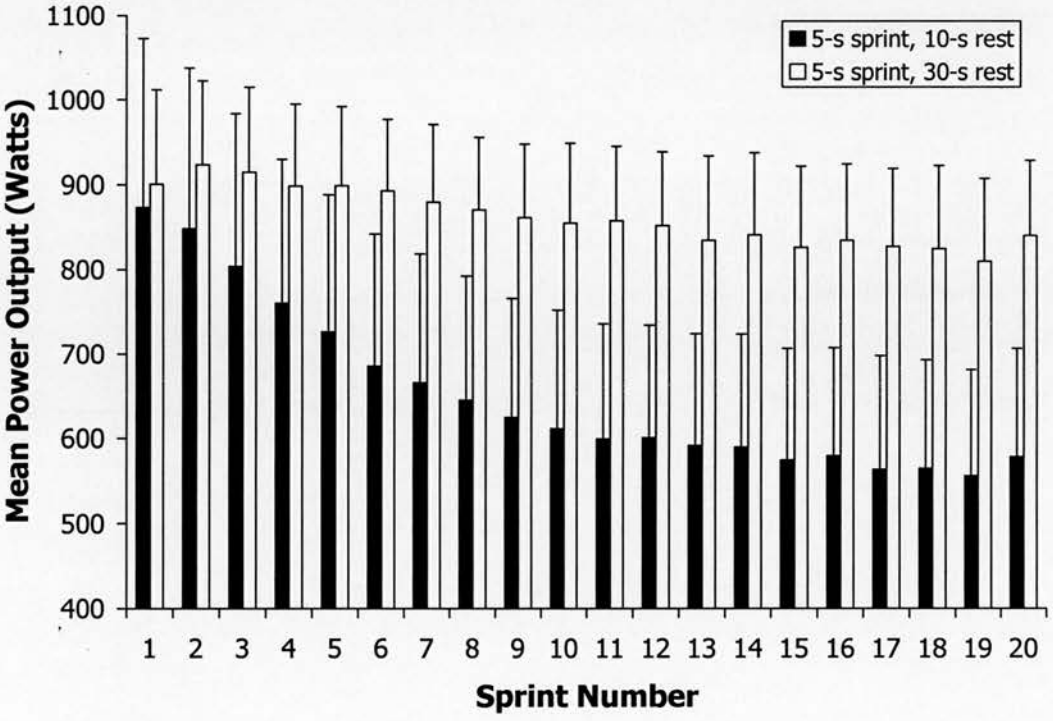


Figure 6.1 Mean power output data during maximal intermittent test protocols using different recovery periods. Values are means; bars are standard deviations.

Table 6.1 The influence of recovery duration on measures of power output during repeated bouts of brief maximal work.

	Recovery duration			
	10 seconds	**30 seconds**	**% Difference**	**95% CL**
PP_{max} (Watts)	1109 ± 143	1152 ± 162	3.9%	1.4% to 6.3%
MP_{max} (Watts)	904 ± 108	942 ± 118	4.2%	2.0% to 6.4%
PP_{mean} (Watts)	827 ± 91	1038 ± 126	25.5%	22.6% to 28.4%
MP_{mean} (Watts)	671 ± 67	854 ± 99	27.3%	24.0% to 30.6%

Note: PP_{max} = maximum peak power; MP_{max} = maximum mean power; PP_{mean} = mean peak power; MP_{mean} = mean mean power; CL = confidence limits.

6.3.2 Fatigue

Mean fatigue scores during protocols 1 and 2 were 25.3 ± 6.0% and 9.2 ± 4.5% respectively. The 95% likely range for the true value of the difference in fatigue between the two protocols was 14.1% to 18.2%.

6.3.3 Oxygen Consumption

Figure 6.2 shows the $\dot{V}O_2$ data for one of the subjects during the two intermittent test protocols. A summary of the group data is presented in Table 6.2. Although mean $\dot{V}O_2$ during the sprints was not substantially different between protocols, there was a 15.9% difference between protocols in mean $\dot{V}O_2$ during recovery (95% likely range: 12.3% to 19.4%).

6.3.4 Respiratory Exchange Ratio

The RER response to the two intermittent protocols is summarised in Table 6.2. Overall, mean RER was 9.3% lower in the sprints (95% likely range: 7.5% to 11.2%), and 6.6% lower in recovery (95% likely range: 4.7% to 7.5%) during Protocol 2. RER data for one subject during the two intermittent test protocols are illustrated in Figure 6.3.

6.3.5 Heart Rate

The effect of recovery duration on heart rate is illustrated in Figure 6.4, with a summary of the group data presented in Table 6.2. Overall, mean heart rates during the sprints were 10.1% higher in Protocol 1 than in Protocol 2 (95% likely range: 7.6% to 12.7%), with similar differences (+6.7%) observed during recovery (95% likely range: 4.9% to 9.1%).

Table 6.2 The influence of recovery duration on $\dot{V}O_2$, RER, and heart rate during repeated bouts of brief maximal work.

	$\dot{V}O_2$ (l.min^{-1})		RER		Heart rate (b.min^{-1})	
Recovery	**Work**	**Rest**	**Work**	**Rest**	**Work**	**Rest**
10 seconds	3.65 ± 0.49	3.09 ± 0.25	1.07 ± 0.05	1.06 ± 0.04	174 ± 9	175 ± 9
30 seconds	3.45 ± 0.92	2.60 ± 0.36	0.97 ± 0.04	0.99 ± 0.04	158 ± 13	164 ± 13

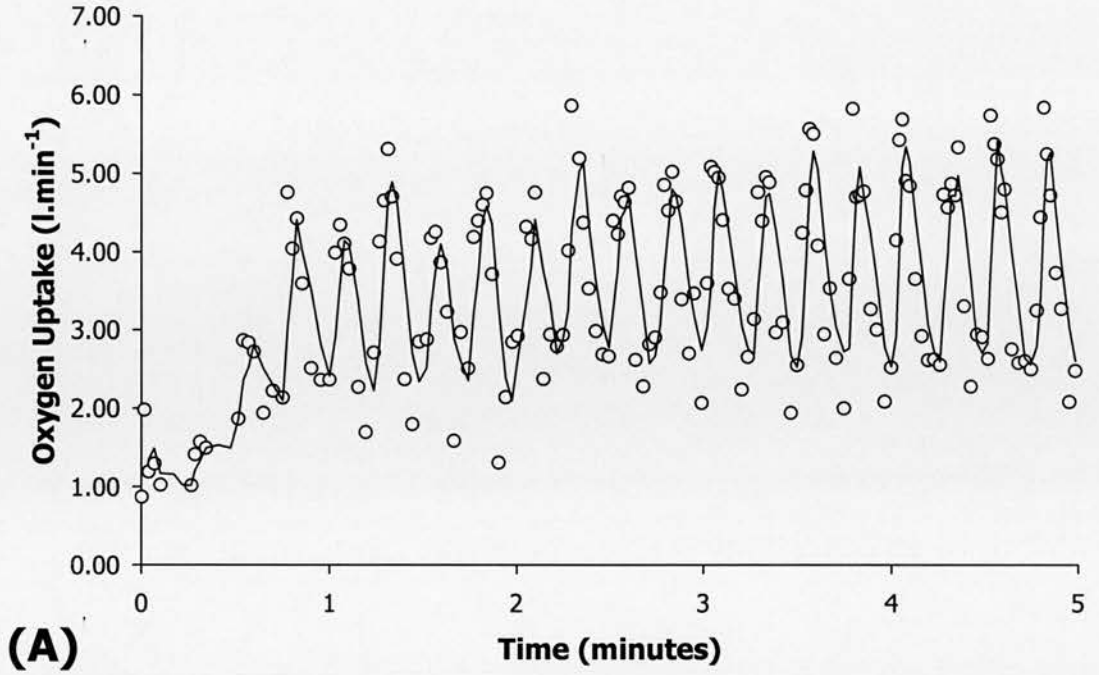
Note: RER = Respiratory exchange ratio.

6.3.6 Blood Lactate

The blood lactate response to the intermittent test protocols is illustrated in Figure 6.5. There were no substantial differences in mean blood lactate concentration between the two protocols at the start of each trial. However, differences of 27% (95% likely range: 14.5% to 38.8%), 29.2% (95% likely range: 21.2% to 37.2%), and 40.2% (95% likely range: 34.6% to 45.7%) were observed after sprint 10, sprint 20, and 5 minutes after each trial respectively.

6.3.7 Ratings of Perceived Exertion

Ratings of perceived exertion increased progressively throughout both intermittent test protocols (see Figure 6.6). Substantial differences between the two protocols in mean RPE of 11.4% (95% likely range: 5.7% to 16.3%), 12.0% (95% likely range: 9.3% to 15.3%), 10.2% (95% likely range: 7.2% to 13.3%), and 8.0% (95% likely range: 4.5% to 11.4%) were observed after sprints 5, 10, 15, and 20 respectively.



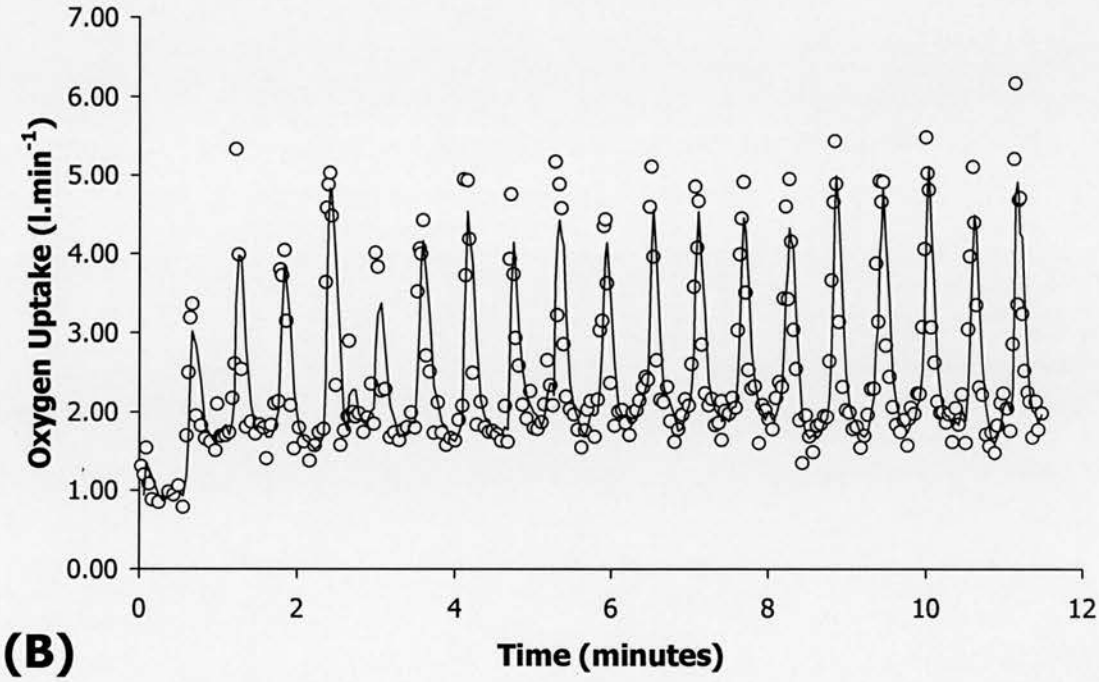
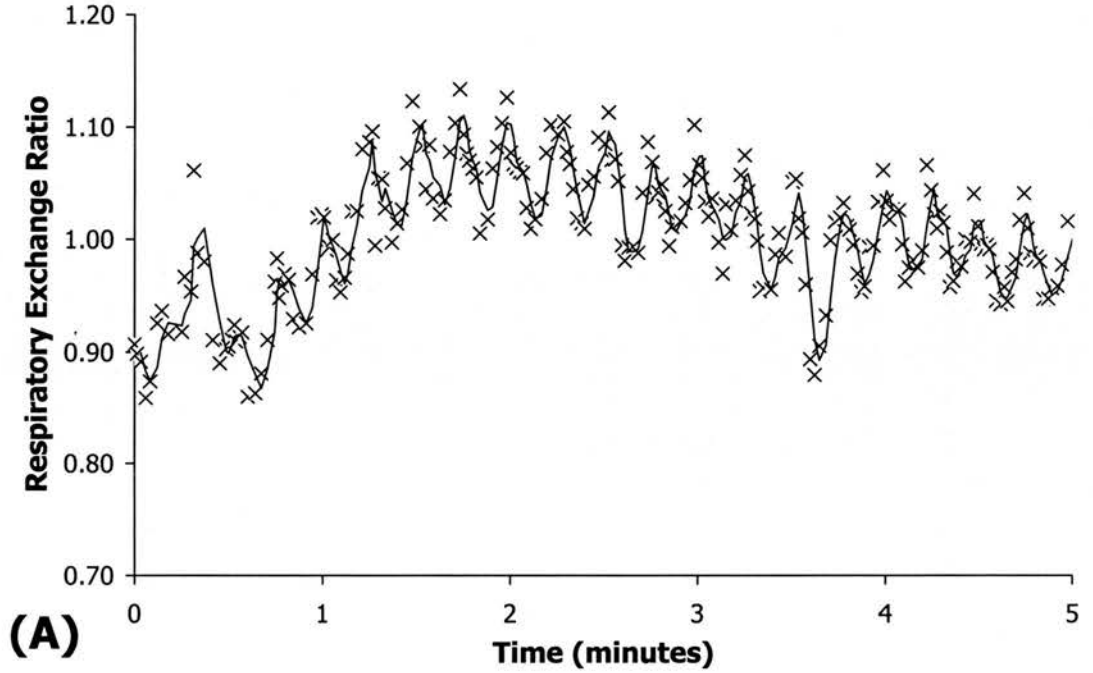


Figure 6.2 Oxygen consumption data for one subject during 20 x 5-s sprint, 10-s rest (A), and 20 x 5-s sprint, 30-s rest (B). Note: Open circles represent breath by breath values of $\dot{V}O_2$, lines represent a three-breath moving average $\dot{V}O_2$.



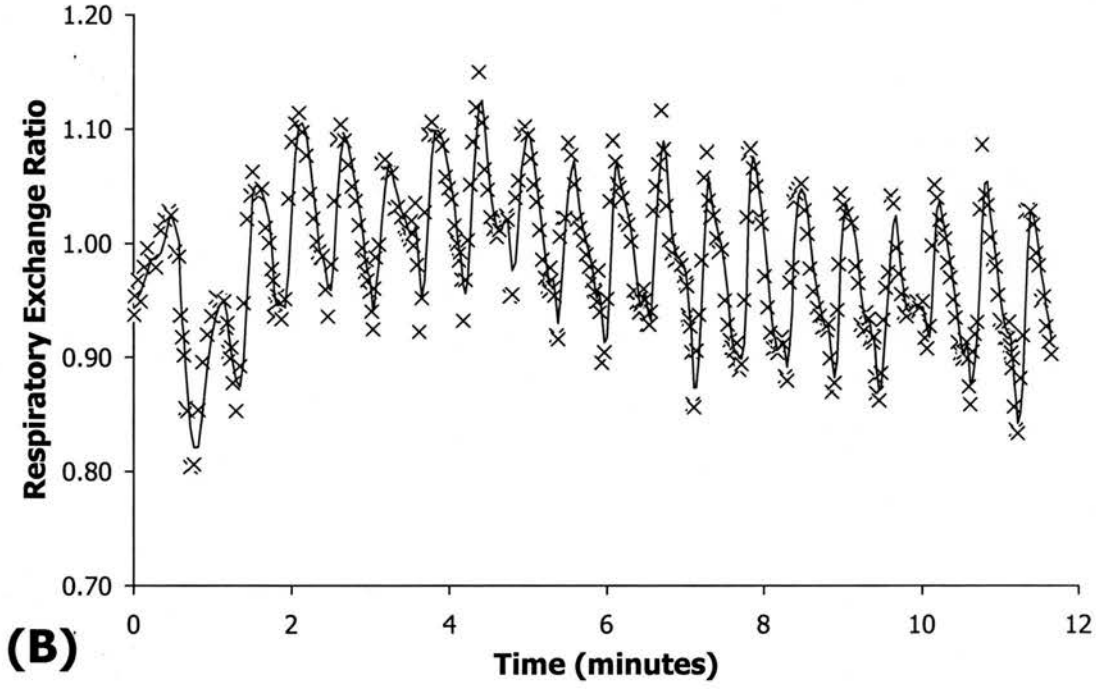
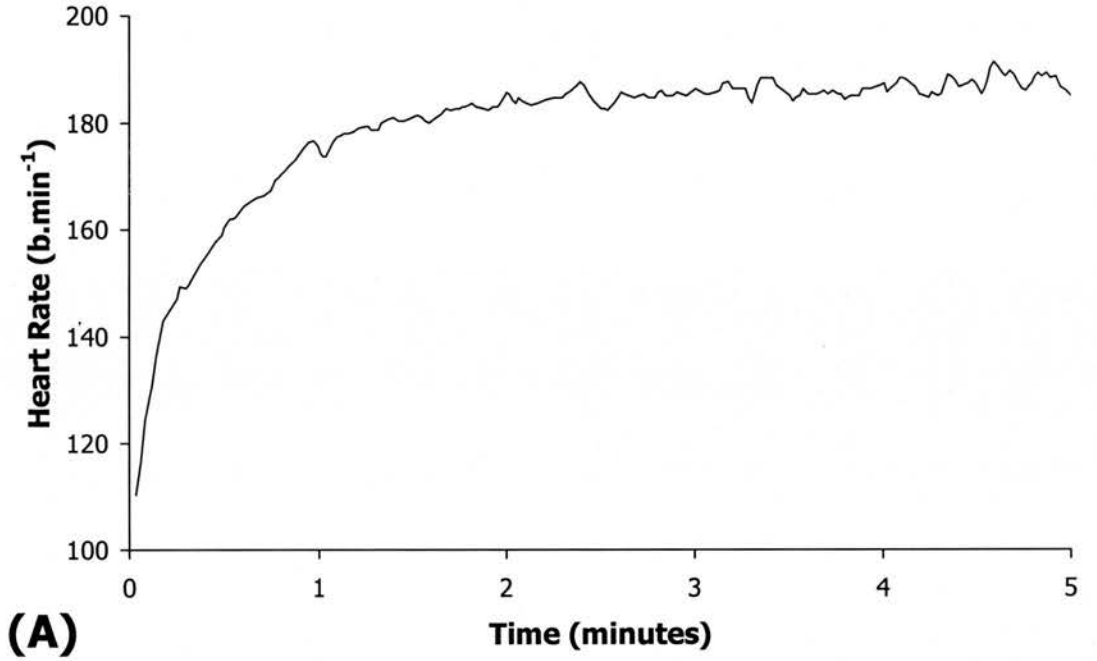


Figure 6.3 Respiratory exchange ratio data for one subject during 20 x 5-s sprint, 10-s rest (A), and 20 x 5-s sprint, 30-s rest (B). Note: Crosses represent breath by breath values of RER, lines represent a three-breath moving average RER.



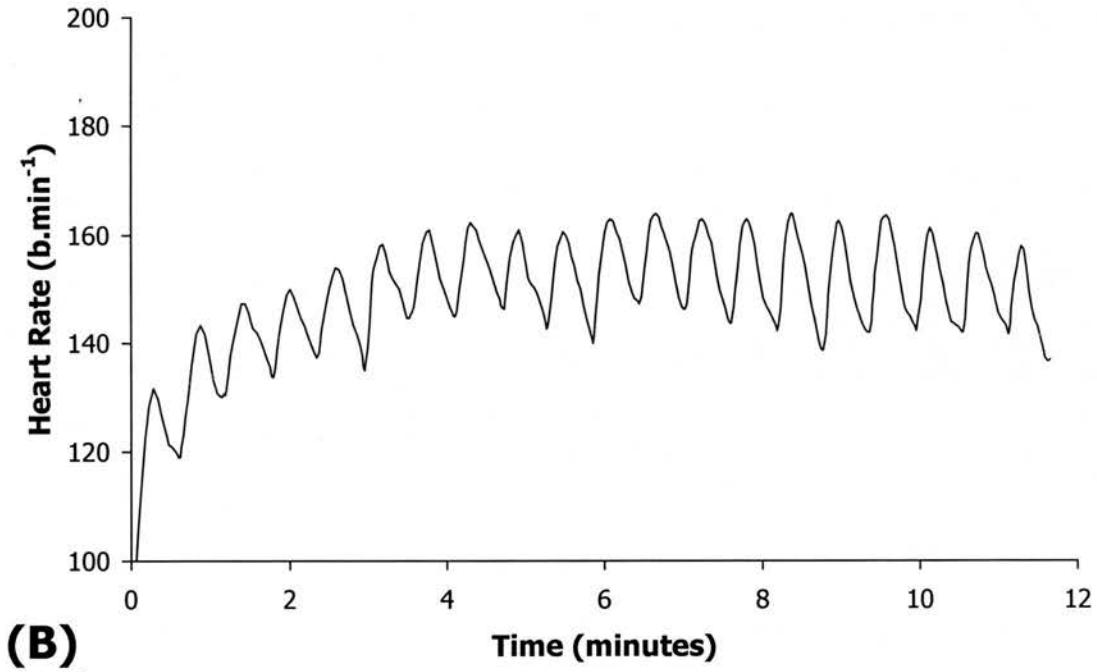


Figure 6.4 Heart rate data for one subject during 20 x 5-s sprint, 10-s rest (A), and 20 x 5-s sprint, 30-s rest (B). Note: Lines represent a three-sample moving average heart rate.

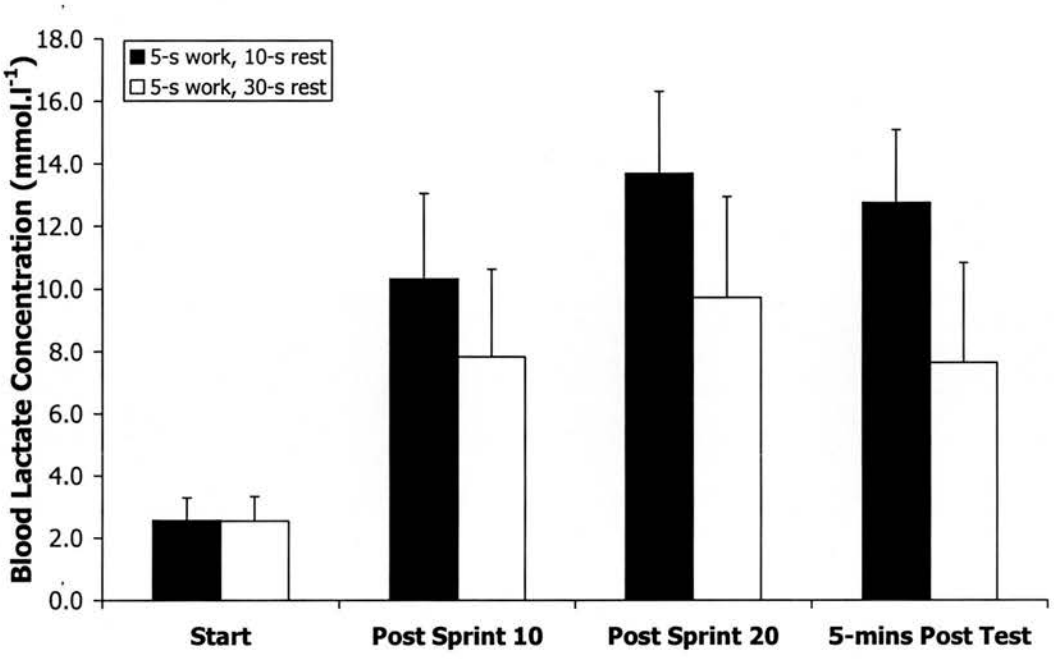


Figure 6.5 The influence of recovery duration on blood lactate during repeated bouts of brief maximal work. Values are means; bars are standard deviations.

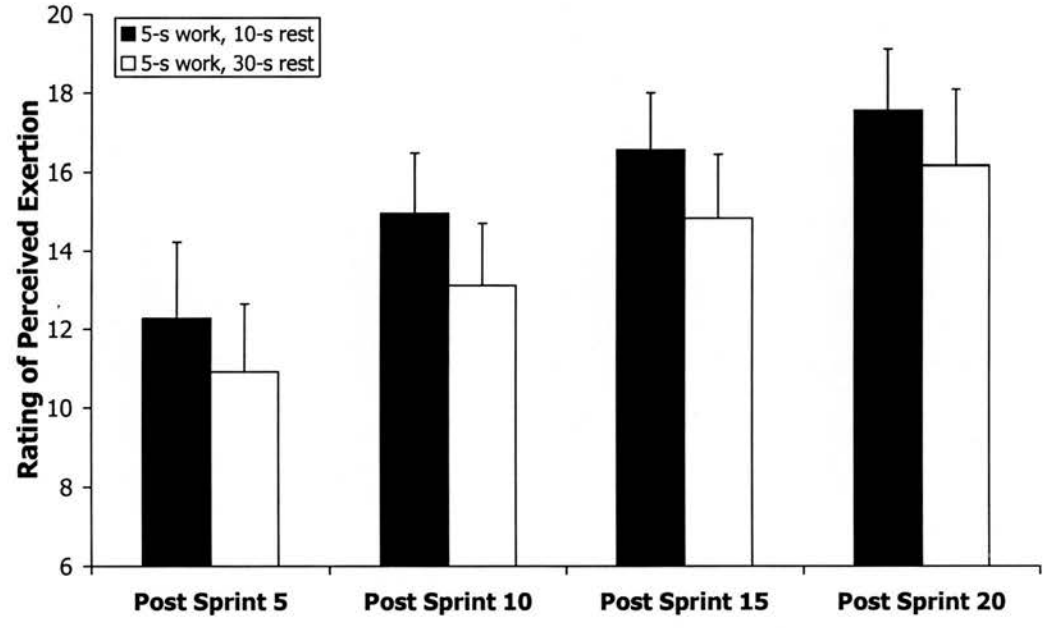


Figure 6.6 The influence of recovery duration on individual ratings of perceived exertion during repeated bouts of brief maximal work. Values are means; bars are standard deviations.

6.4 Discussion

The aim of this investigation was to examine the influence of recovery duration (10-s and 30-s) on various measures of brief maximal intermittent performance. Recovery duration had a substantial effect on measures of maximum (PP_{max} and MP_{max}) and mean power output (PP_{mean} and MP_{mean}), with differences in the former appearing to be the result of the potentiation effect that occurred during the first few sprints in Protocol 2. Short-term potentiations of power output are also evident in a number of previous investigations into this type of work (Brooks *et al.*, 1990; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988; Robinson *et al.*, 1995; Stone *et al.*, 1999) although the aetiology of this response remains uncertain (Abbate *et al.*, 2000; Güllich & Schmidtbleicher, 1996; Smith *et al.*, 2001). The lack of any potentiation of power output in Protocol 1 suggests that the 10-s recovery periods provided insufficient restoration of homeostasis to allow the effect to occur.

The substantial difference in mean power output between the two intermittent protocols reflects the considerable influence of recovery duration on fatigue. Moreover, in Protocol 2, subjects were able to maintain a high power output despite a high level of metabolic acidosis. Increased hydrogen ion concentrations are reported to interfere with the activity of various enzymes involved in the ATP generating processes. However, the recovery of maximal power output is associated primarily with the resynthesis of PCr (Bergström & Hultman, 1991; Bogdanis *et al.*, 1995; Hitchcock *et al.*, 1989; Holmyard *et al.*, 1994; Sahlin & Ren, 1989), the initial phase of which appears to be unaffected by the metabolic environment (Roussel *et al.*, 2000; Sahlin *et al.*, 1979; Walter *et al.*, 1997). Although the availability of PCr may be a limiting factor in performance even before PCr stores are totally depleted (Sahlin *et al.*, 1998), it is likely that the 30-s recovery periods of Protocol 2 enabled PCr degradation to make a sizeable contribution to ATP resynthesis throughout each work period. Phosphocreatine degradation has previously been reported to account for 80% of the total anaerobic ATP provision during the final bout of 10 x 6-s maximal sprints (30-s recoveries) (Gaitanos *et al.*, 1993). In contrast, with a reported half-time for PCr resynthesis of $\geq$ 22 seconds (Bogdanis *et al.*, 1995; Harris *et al.*, 1976; Laurent *et al.*, 1992; McCully *et al.*, 1989), it is unlikely that the 10-s recovery periods of Protocol 1 would have been sufficient to allow PCr degradation to maintain a sizeable contribution to power output beyond the first few sprints.

The idea that power output during the intermittent test protocols was regulated predominantly by PCr availability provides the most likely explanation for the substantial between-protocol differences in blood lactate. In effect, the reduced PCr availability associated with Protocol 1 would place greater demands on anaerobic glycolysis to maintain the required rate of ATP provision. Although recovery duration also influences the removal of lactate, the half-time for this process is approximately 9 minutes (Metzger & Fitts, 1987; Sahlin *et al.*, 1976), and would therefore have little effect during the short recovery periods of the current study. Previous investigations into the physiological response to maximal intermittent work have reported an apparent inhibition of glycolysis with repeated sprints (Bangsbo, 1996; Gaitanos *et al.*, 1993; McCartney *et al.*, 1986; Parolin *et al.*, 1999; Putman *et al.*, 1995; Spriet *et al.*, 1989). Although blood lactate is only a reflection of the balance between lactate production and clearance, the progressive increase in blood lactate throughout both intermittent test protocols supports the need for further investigation into the full extent of glycolytic inhibition during this type of work.

One of the most startling contrasts between the two intermittent test protocols occurred in the heart rate response. In Protocol 2, the pattern of the heart rate response was similar to that previously reported for 10 x 6-s maximal treadmill sprints interspersed with 30-s recovery periods (Holmyard *et al.*, 1988). In contrast, the heart rate response to Protocol 1 was much more like that of a continuous exercise protocol. Although the 10-s recovery periods provided insufficient time for any appreciable recovery of heart rate between sprints, the same effect was absent from the $\dot{V}O_2$ and RER responses to the protocol. This finding has implications for those studies that have used submaximal heart rate-$\dot{V}O_2$ relationships to estimate the oxygen cost of various sporting activities (Boyle *et al.*, 1994; Christmass *et al.*, 1998; Lothian & Farrally, 1995).

The kinetics of $\dot{V}O_2$ during recovery are bi-phasic, characterised by an initial rapid decline in $\dot{V}O_2$, followed by a much slower phase lasting up to several hours (Bahr *et al.*, 1987; Bangsbo *et al.*, 1991a). In this investigation, the difference in $\dot{V}O_2$ between the two test protocols was the result of the extended recovery time provided by Protocol 2. Since PCr resynthesis is achieved exclusively via aerobic ATP resynthesis (Blei *et al.*, 1993; Harris *et al.*, 1976; Quistorff *et al.*, 1992; Sahlin *et al.*, 1979), this finding adds further support to the

idea that between-protocol differences in mean power output were most likely due to differences in the magnitude of the PCr contribution to the sprints.

Although substantial between-protocol differences in $\dot{V}O_2$ were only observed during the recovery periods, differences in RER were observed during sprints and recovery periods. Since $\dot{V}O_2$ during the sprints was unaffected by recovery duration, differences in RER were most likely the result of differences in $\dot{V}CO_2$ as a consequence of lactate and hydrogen ion buffering.

Finally, differences in fatigue between the two protocols reflect, to some extent, differences in the RPE response. However, despite the minimal amount of fatigue experienced in Protocol 2, individual ratings of perceived exertion increased steadily throughout the test to levels rated as somewhere between "hard" and "very hard". Although progressive increases in various metabolic by-products (i.e. ammonia, lactate, potassium, etc) provide a likely explanation, it is difficult to elucidate the precise cause of this response.

6.5 Conclusions

All in all, the results of this investigation illustrate the considerable influence of recovery duration on various measures of brief maximal intermittent work, Although the precise role of PCr during this type of work remains somewhat elusive due to the invasive nature of muscle biopsy procedures and the inability of ^{31}P magnetic resonance spectroscopy techniques to examine the large muscle masses involved in this type of work, longer recovery periods resulted in improvements in performance which were most likely mediated by an enhanced PCr contribution to ATP resynthesis during the work periods.

7. THE RELATIONSHIP BETWEEN AEROBIC AND ANAEROBIC PARAMETERS AND PERFORMANCE DURING SHORT-DURATION MAXIMAL-INTENSITY INTERMITTENT CYCLING.

7.1 Introduction

Research into the physiological demands of sports with intermittent activity patterns suggests that these events place considerable demands on aerobic and anaerobic pathways (Nicholas, 1997; Reilly & Borrie, 1992). However, investigations into relationships between sport-specific repeat sprint performance indices and physiological parameters show conflicting results (Aziz *et al.*, 2000; Bishop *et al.*, 1999; Dawson *et al.*, 1993; Wadley & Le Rossignol, 1998). Moreover, although MAOD is regarded by many as the best non-invasive measure of anaerobic capacity (Green, 1995; Maxwell & Nimmo, 1996; Saltin, 1990; Spriet, 1995; Weyand *et al.*, 1993), few studies have used this technique to assess relationships between anaerobic capacity and various measures of sport-specific repeat sprint performance. The purpose of this particular investigation was to address these issues by examining: a) how the physiological variables of $\dot{V}O_{2max}$ and MAOD correlated with several performance indices during repeated bouts of brief maximal work; and b) how recovery duration influenced the magnitude of those relationships.

7.2 Methods

7.2.1 Subject Group

Twenty-five male physical education and sport science students from the University of Edinburgh volunteered to participate in the study. The means ± standard deviation (SD) for age, height, body mass, and predicted percentage body fat (Jackson & Pollock, 1978) were: 20.6 ± 1.5 years, 177.2 ± 5.4 cm, 78.2 ± 8.2 kg, and 11.9 ± 4.7% respectively. Ethical approval was granted by the University of Edinburgh and all subjects gave their written informed consent prior to participation. Prior to commencement all subjects completed a training history questionnaire, which indicated that all were recreational athletes who had been actively involved in sport for an average of approximately thirteen years.

7.2.2 Research Design

Each subject completed four separate physiological test protocols and each protocol was separated by a minimum 24-hour recovery period. Protocol 1 consisted of twenty 5-s sprints

separated by 10-s recovery periods (W:R = 1:2). Protocol 2 consisted of twenty 5-s sprints separated by 30-s recovery periods (W:R = 1:6). Protocol 3 was an incremental test to determine $\dot{V}O_{2max}$. Protocol 4 was a MAOD test to assess anaerobic capacity. Subjects were asked to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each test, and to refrain from strenuous exercise 24-hours before each test.

7.2.3 Equipment

All test protocols were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was interfaced with a computer to enable high-frequency logging of the flywheel angular velocity. The ergometer was fitted with standard toe-clips and straps and secured to the floor of the laboratory. Apart from the $\dot{V}O_{2max}$ test in which the initial intensity served as a warm-up, each test protocol was preceded by a 5-minute warm-up on the ergometer at 60 revolutions per minute (rpm) against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the tests was determined for each subject before the first test and remained constant for all subsequent tests.

Metabolic gases were analysed using an automated on-line breath-by-breath gas analysis system (Vista Mini CPX; Gold Edition, Vacu-Med, California). The analyser was calibrated before every test using oxygen and carbon dioxide gases of known concentrations (BOC gases, UK) and the flowmeter was calibrated using a 3-litre syringe (Vacu-Med, California). During the tests subjects breathed room air through a facemask (Vacu-Med, California) that was secured in place by a head cap assembly (Hans Rudolph, USA). Heart rate data were monitored continuously throughout the tests by means of short-range radio telemetry (Sport-tester, Polar Electro Oy, Finland). The gas analyser was interfaced with a computer that provided on-line information (breath-by-breath) on $\dot{V}O_2$, $\dot{V}CO_2$, respiratory exchange ratio (RER), and heart rate.

7.2.4 Maximal Intermittent Test Protocols

Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s) the methodology for both maximal intermittent test protocols was the same. The flywheel resistance for all tests was set at 0.075 kg.kg body mass^{-1} and flywheel rotations were sampled at a frequency of 18.2 Hz. In accordance with the results of Study I and the

recommendations made by Capriotti *et al.* (1999), all subjects completed 2 familiarisation trials of both intermittent test protocols prior to commencement of the study.

Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the test. After a further 3-minute stationary rest period, the test began. Prior to each test subjects were instructed to remain seated in the saddle for the duration of the test, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort.

Subjects were given a 5-s countdown before each sprint; the start and finish of which were indicated by a computer-generated audio signal. Subjects were verbally encouraged to give a maximal effort during every sprint. After the final sprint, subjects cycled at 60 rpm for 5-minutes against a flywheel resistance of 1.0 kg. A metronome (Seiko, UK) was used to indicate the cadence for this part of the test.

Power outputs during each sprint were corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data, performance measures of peak power output (PP) and mean power output (MP) were calculated for each sprint. Power output data across each intermittent test protocol were derived as measures of maximum PP (PP_{max}), maximum MP (MP_{max}), mean PP (PP_{mean}), and mean MP (MP_{mean}). In accordance with the results of Study II, fatigue during each test was calculated from MP using the performance decrement score devised by Fitzsimons *et al.* (1993):

Performance Decrement Calculation

Fatigue = 100 – ((Total power output ÷ Ideal power output) x 100)

Where:

Total Power Output = sum of MP values from all sprints.

Ideal Power Output = number of sprints x MP_{max}.

7.2.5 Maximal Aerobic Power

Maximal aerobic power was assessed using a modified version of the protocol used by Doherty *et al.* (2000). A metronome and two separate digital readouts were used to help the tester and the subjects ensure that a constant cadence of 80 rpm was observed for all stages of the test. The test began with three 7-minute exercise bouts of increasing intensity (80W, 120W, and 160W), with 5 minutes rest between bouts. Immediately after the third bout, the intensity was increased by 40W every 2-minutes until subjects reached volitional exhaustion. $\dot{V}O_{2max}$ was determined as the highest 20-breath average $\dot{V}O_2$ observed during the test provided that at least two of the following criteria had been met:

- A plateau in $\dot{V}O_2$ at volitional exhaustion.
- An RER value ≥ 1.10
- A maximum heart rate of 220 – age ($\pm$ 10 $b.min^{-1}$)

7.2.6 Maximal Accumulated Oxygen Deficit

Oxygen consumption during the final two minutes of each of the 7-minute submaximal stages of the maximal aerobic power test, together with a fixed y-intercept of 5 $ml.kg^{-1}.min^{-1}$ (Medbø *et al.*, 1988) were used to develop linear regression equations of $\dot{V}O_2$ versus power output for each subject. The intensity for the MAOD test (110% of the power output required to elicit $\dot{V}O_{2max}$) was calculated by extrapolation of this regression equation.

After the warm-up subjects were given 5-minutes stationary rest before the start of the test. Prior to the test subjects were informed that they should attempt to reach the required cadence of 80 rpm as soon as possible and to maintain this cadence for as long as possible. Two digital readouts and a metronome were used to assist the subjects and the tester. The test was terminated once subjects were no longer able to maintain the required cadence.

Oxygen consumption and heart rate were monitored continuously (breath-by-breath) throughout each test. After allowing 5-s from the start of each test to give subjects time to reach the required cadence, the total oxygen consumption during each test was calculated. Maximal accumulated oxygen deficit (calculated in O_2 equivalents) was determined from the difference between the predicted oxygen demand of the exercise (as determined from the

aforementioned regression equation) and the actual oxygen consumption. No adjustment was made in MAOD values for the aerobic component of MAOD (stored oxygen).

7.2.7 Data Analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Measures of centrality and spread are presented as means ± SD. Pearson correlation coefficients were used to determine relationships between physiological parameters and performance indices after normalising values for body mass. Correlation coefficients were interpreted in accordance with the following scale of magnitudes as devised by Cohen (1988): $r < 0.1$ is trivial; $0.1 \leq r < 0.3$ is small; $0.3 \leq r < 0.5$ is moderate; $r \geq 0.5$ is large. Confidence limits (95%) were calculated using the methods outlined by Fisher (1921).

7.3 Results

Mean values of $\dot{V}O_{2max}$ and MAOD were 52.0 ± 4.6 $ml.kg^{-1}.min^{-1}$ and 50.7 ± 9.1 mlO_2 $eq.kg^{-1}$, respectively. Correlation coefficients for the linear regressions used to determine the intensities for the MAOD tests had a mean value of $r = 0.99 \pm 0.02$. Power output data from the intermittent test protocols are summarised in Table 7.1. Correlation coefficients between power output data and the physiological variables of $\dot{V}O_{2max}$ and MAOD are presented in Table 7.2.

Table 7.1 Power output data during maximal intermittent test protocols.

	Peak Power Data (Watts)		**Mean Power Data (Watts)**	
	PP_{max}	**PP_{mean}**	**MP_{max}**	**MP_{mean}**
Protocol 1[a]	1109 ± 143	827 ± 91	904 ± 108	671 ± 67
Protocol 2[b]	1152 ± 162	1038 ± 126	942 ± 118	854 ± 99

Note: a = 20 x 5-s sprint, 10-s rest; b = 20 x 5-s sprint, 30-s rest; PP_{max} = maximum peak power; PP_{mean} = mean peak power; MP_{max} = maximum mean power; MP_{mean} = mean mean power.

Fatigue scores for the intermittent test protocols were 25.3 ± 6.0% (Protocol 1), and 9.2 ± 4.5% (Protocol 2). Correlation coefficients between fatigue and $\dot{V}O_{2max}$ in Protocols 1 and 2 respectively were –0.18 (95% likely range: 0.23 to –0.54), and –0.34 (95% likely range: 0.06 to –0.65). Correlation coefficients between fatigue and MAOD were trivial.

Table 7.2 Correlation coefficients between power output data and physiological parameters during repeated bouts of brief maximal work with contrasting recovery periods.

	Peak Power Data (Watts.kg^{-1})				**Mean Power Data (Watts.kg^{-1})**			
	PP_{max}		**PP_{mean}**		**MP_{max}**		**MP_{mean}**	
Protocol	1	2	1	2	1	2	1	2
$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	0.32	0.47	0.67	0.60	0.47	0.45	0.67	0.61
Lower CL	*-0.09*	*0.09*	*0.37*	*0.27*	*0.09*	*0.07*	*0.37*	*0.28*
Upper CL	*0.63*	*0.73*	*0.84*	*0.80*	*0.73*	*0.72*	*0.84*	*0.81*
MAOD (mlO_2 eq.kg^{-1})	0.42	0.51	0.50	0.46	0.31	0.46	0.43	0.44
Lower CL	*0.03*	*0.14*	*0.13*	*0.08*	*-0.10*	*0.08*	*0.04*	*0.05*
Upper CL	*0.70*	*0.75*	*0.75*	*0.72*	*0.63*	*0.72*	*0.71*	*0.71*

Note: CL = 95% Confidence limits; MAOD = Maximal accumulated oxygen deficit; O_2 eq = Oxygen equivalents; PP_{max} = maximum peak power; PP_{mean} = mean peak power; MP_{max} = maximum mean power; MP_{mean} = mean mean power.

7.4 Discussion

Research into sports with intermittent activity patterns suggests that these events place considerable demands on aerobic and anaerobic pathways (Nicholas, 1997; Reilly & Borrie, 1992). This idea is supported by the $\dot{V}O_{2max}$ and MAOD values of athletes involved in sports with intermittent activity patterns, the values of which are typically less than those of endurance and sprint trained athletes respectively (Gastin & Lawson, 1994). The purpose of this investigation was to examine: a) how the physiological variables of $\dot{V}O_{2max}$ and MAOD correlated with several performance indices during maximal sport-specific intermittent work; and b) how recovery duration influenced the magnitude of those relationships.

In an attempt to limit the potential for pacing, previous investigations into the relationships between physiological variables and performance during this type of sport-specific intermittent work have used test protocols with a small number ($\leq$ 12) of sprints. Although differences in maximum power output between the two intermittent test protocols in this investigation suggest a possible pacing effect, the results of Study III suggest that differences of this kind are more likely to be the result of between-protocol differences in short-term potentiations of power output.

In the present investigation moderate to large positive correlations were observed between $\dot{V}O_{2max}$ and power output data, with similar values observed between the two intermittent

protocols. Moreover, the strength of the relationship increased as values were averaged over all 20 sprints, supporting previous reports of moderate negative correlations between $\dot{V}O_{2max}$ and total intermittent sprint time (Aziz *et al.*, 2000; Dawson *et al.*, 1993). The aerobic component of a single short sprint (≤ 10-s) is reported to be very small (< 10%) (Bangsbo *et al.*, 2001; Parolin *et al.*, 1999). Therefore, the relationship between $\dot{V}O_{2max}$ and maximum power output (PP_{max} and MP_{max}) was not expected and is somewhat contrary to previous reports (Aziz *et al.*, 2000). However, when sprints are repeated the aerobic component to each sprint is reported to increase progressively (Bogdanis *et al.*, 1998; Gaitanos *et al.*, 1993), supporting the larger correlations observed between $\dot{V}O_{2max}$ and mean power output (PP_{mean} and MP_{mean}).

The presence of moderate correlations between MAOD and power output data was as expected. Gaitanos *et al.* (1993) reported that most of the ATP during a 6-s maximal sprint was derived equally from PCr degradation and anaerobic glycolysis. However, as sprints were repeated (30-s recoveries), the relative percentage contribution from PCr increased, whilst that of anaerobic glycolysis decreased. This apparent inhibition of glycolysis with repeated sprints has been observed in a number of studies (Bangsbo, 1996; Gaitanos *et al.*, 1993; McCartney *et al.*, 1986; Parolin *et al.*, 1999; Putman *et al.*, 1995; Spriet *et al.*, 1989) and is suggested to be offset to some extent by the increase in aerobic ATP provision (Bogdanis *et al.*, 1998; Gaitanos *et al.*, 1993). The fact that energy from PCr degradation represents approximately 30% (Medbø *et al.*, 1988) of an individual's total anaerobic capacity is a possible explanation as to why correlations between MAOD and power output were only moderate.

Although MAOD is regarded by many as the best non-invasive measure of anaerobic capacity (Green, 1995; Maxwell & Nimmo, 1996; Saltin, 1990; Spriet, 1995; Weyand *et al.*, 1993), only one previous study has used MAOD to investigate the relationship between anaerobic capacity and maximal intermittent performance (Wadley & Le Rossignol, 1998). Despite differences in methodology (12 x 20m sprints, 20-s recoveries), the moderate negative correlations reported between MAOD and total intermittent sprint time corroborate the findings of the present study.

The only variable to show a substantial correlation with fatigue in this investigation was $\dot{V}O_{2max}$. Fatigue during repeated bouts of brief maximal work is associated predominantly with changes in the intramuscular environment the causative factors of which include reduced rates of ATP provision and impaired excitation-contraction coupling (Hultman *et al.*, 1990). Although fatigue during intermittent work has been shown to be influenced by oxygen availability (Balsom *et al.*, 1994a; Balsom *et al.*, 1994b), evidence to support a link between $\dot{V}O_{2max}$ and fatigue is far from substantial (Aziz *et al.*, 2000; Bishop *et al.*, 1999; Dawson *et al.*, 1993; Wadley & Le Rossignol, 1998). Moreover, investigations into the influence of $\dot{V}O_{2max}$ on potential causative factors of muscular fatigue show contradictory results, For example, many authors regard PCr availability as the major limiting factor in the development of fatigue during brief maximal intermittent work (Bergström & Hultman, 1991; Bogdanis *et al.*, 1995; Cherry *et al.*, 1998; Hitchcock, 1989; Holmyard *et al.*, 1994; Sahlin & Ren, 1989; Sargeant & Dolan, 1987). Moreover, PCr resynthesis is reported to occur exclusively via aerobic metabolism (Blei *et al.*, 1993; Harris *et al.*, 1976; Quistorff *et al.*, 1992; Sahlin *et al.*, 1979). However, whilst some studies have reported a strong association between $\dot{V}O_{2max}$ and the rate of post-exercise PCr resynthesis (Bogdanis *et al.*, 1996; Takahashi *et al.*, 1995), others show contradictory findings (Cooke *et al.*, 1997). Despite the lack of definitive physiological evidence to support a link between $\dot{V}O_{2max}$ and fatigue during brief maximal intermittent work, smaller decrements in repeat sprint ability (10 x 6-s sprint, 30-s rest) have been observed in endurance athletes ($\dot{V}O_{2max}$: 60.8 ± 4.1 $ml.kg^{-1}.min^{-1}$) in comparison to games players ($\dot{V}O_{2max}$: 52.5 ± 4.9 $ml.kg^{-1}.min^{-1}$) (Hamilton *et al.*, 1991). Although the results of this investigation provide some support for a link between $\dot{V}O_{2max}$ and the development of fatigue during brief maximal intermittent work, the fact that the only sizeable correlations were in Protocol 2 suggests that the magnitude of that association is largely determined by recovery duration.

Although many of the variables examined in this investigation show moderate to large correlations, in most cases the confidence limits allow for the fact that the true magnitude of those relationships could be anything from trivial to very large. This same problem is also evident in previous research in this area (Aziz *et al.*, 2000; Bishop *et al.*, 1999; Dawson *et al.*, 1993; Wadley & Le Rossignol, 1998). All in all, considering the large number of subjects required to establish a reasonable level of precision with correlations of the magnitude observed in this investigation, it would be wise to focus future research into

examining how changes in $\dot{V}O_{2max}$ and MAOD directly influence performance during this type of intermittent work.

7.5 Conclusions

The physiological variables of $\dot{V}O_{2max}$ and MAOD demonstrated moderate to large correlations with performance measures during maximal, sport-specific intermittent work. Apart from fatigue, the magnitude of those relationships were largely unaffected by recovery duration.

8. THE INFLUENCE OF ENDURANCE TRAINING ON SHORT-DURATION MAXIMAL-INTENSITY INTERMITTENT CYCLING PERFORMANCE.

8.1 Introduction

Following on from the previous investigation of this thesis, the purpose of this final investigation was to investigate how improvements in aerobic fitness, as a result of six weeks of endurance training, would influence brief maximal intermittent sprint performance. To this end, a training programme was designed to enhance $\dot{V}O_{2max}$ whilst having little or no effect on anaerobic capacity. Six weeks of continuous training at 70% of the power output required to elicit $\dot{V}O_{2max}$ has previously been shown to produce such a response (Tabata *et al.*, 1996).

8.2 Methods

8.2.1 Subject Group

Twenty-one male physical education and sport science students from the University of Edinburgh volunteered to participate in the study. Ethical approval was granted by the University of Edinburgh and all subjects gave their written informed consent prior to participation. Prior to commencement all subjects completed a training history questionnaire (Appendix A1.5), which indicated that all were recreational athletes who had been actively involved in sport for an average of approximately thirteen years. All subjects were randomly assigned to either an experimental (n = 12) or a control (n = 9) group. The homogeneity of the subject group permitted a greater number of subjects to be allocated to the experimental group to allow for the potentially increased risk of dropout through injury. Means ± standard deviation (SD) for age, height, body mass, and predicted percentage body fat (Jackson & Pollock, 1978) were as follows (see Table 8.1):

Table 8.1 Subject characteristics

Group	n	Age (years)	Height (cm)	Body mass (kg)	Body fat (%)
Experimental	12	20.3 ± 1.3	174.6 ± 5.6	78.4 ± 9.2	11.8 ± 5.3
Control	9	21.1 ± 1.9	181.2 ± 3.2	78.7 ± 5.6	11.0 ± 4.0

8.2.2 Research Design

Each subject completed four separate physiological test protocols and each protocol was separated by a minimum 24-hour recovery period. Protocol 1 consisted of twenty 5-s sprints separated by 10-s recovery periods (W:R = 1:2). Protocol 2 consisted of twenty 5-s sprints separated by 30-s recovery periods (W:R = 1:6). Protocol 3 was an incremental test to determine $\dot{V}O_{2max}$. Protocol 4 was a maximal accumulated oxygen deficit (MAOD) test to assess anaerobic capacity. Subjects were asked to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each test, and to refrain from strenuous exercise 24-hours before each test.

After the initial round of testing, subjects in the experimental group performed six weeks of endurance training. All subjects were instructed to continue with their normal recreational activities throughout the entire training period. All test protocols were repeated at the end of the training period.

8.2.3 Equipment

All test protocols were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was interfaced with a computer to enable high-frequency logging of the flywheel angular velocity. The ergometer was fitted with standard toe-clips and straps and secured to the floor of the laboratory. Apart from the $\dot{V}O_{2max}$ test in which the initial intensity served as a warm-up, each test protocol was preceded by a 5-minute warm-up on the ergometer at 60 revolutions per minute (rpm) against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the tests was determined for each subject before the first test and remained constant for all subsequent tests.

Respiratory gases were analysed using an automated on-line breath-by-breath gas analysis system (Vista Mini CPX; Gold Edition, Vacu-Med, California). The analyser was calibrated before every test using oxygen and carbon dioxide gases of known concentrations (BOC gases, UK) and the flowmeter was calibrated using a 3-litre syringe (Vacu-Med, California). During the tests subjects breathed room air through a facemask (Vacu-Med, California) that was secured in place by a head cap assembly (Hans Rudolph, USA). Heart rate data were monitored continuously throughout the tests by means of short-range radio telemetry (Sport-tester, Polar Electro Oy, Finland). The gas analyser was interfaced with a computer that

provided on-line information (breath-by-breath) on $\dot{V}O_2$, $\dot{V}CO_2$, respiratory exchange ratio (RER), and heart rate.

Blood lactate concentrations were assessed using a hand-held Lactate Pro (Arkray: KDK, Japan). The reliability ($r = 0.99$) and validity of this equipment has previously been reported (Pyne *et al.*, 2000). The analyser was cleaned and calibrated in accordance with the manufacturers instructions. All blood samples were drawn from a hyperaemised earlobe.

8.2.4 Maximal Intermittent Test Protocols

Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s) the methodology for both maximal intermittent test protocols was the same. The flywheel resistance for all tests was set at 0.075 kg.kg body mass^{-1} and flywheel rotations were sampled at a frequency of 18.2 Hz. In accordance with the the results of Study I and the recommendations made by Capriotti *et al.* (1999), subjects completed two familiarisation trials of both intermittent test protocols prior to commencement of the study. The design and test-retest reliability of these protocols is as previously reported (see Studies I & II).

Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the test. After a further 3-minute stationary rest period, the test began. Prior to each test subjects were instructed to remain seated in the saddle for the duration of the test, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort.

Subjects were given a 5-s countdown before each sprint; the start and finish of which were indicated by a computer-generated audio signal. Subjects were verbally encouraged to give a maximal effort during every sprint. After the final sprint, subjects cycled at 60 rpm for 5-minutes against a flywheel resistance of 1.0 kg. A metronome (Seiko, UK) was used to indicate the cadence for this part of the test.

Blood lactate measurements were taken immediately before the first sprint, after sprint 10, after sprint 20, and 5-minutes post-test. Individual ratings of perceived exertion (RPE) were monitored during each test using a 15-point scale (Borg, 1970). RPE readings were taken after sprints 5, 10, 15, and 20.

Power outputs during each sprint were corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data, measures of peak power output (PP) and mean power output (MP) were calculated for each sprint. Power output data across each intermittent test protocol were derived as measures of maximum PP (PP_{max}), maximum MP (MP_{max}), mean PP (PP_{mean}), and mean MP (MP_{mean}). In accordance with the results of Study II, fatigue during each test was calculated from MP using the performance decrement score devised by Fitzsimons *et al.* (1993):

Performance Decrement Calculation

Fatigue = 100 – ((Total power output ÷ Ideal power output) x 100)

Where:

Total Power Output = sum of MP values from all sprints.

Ideal Power Output = number of sprints x MP_{max}.

8.2.5 Maximal Oxygen Uptake

Maximal oxygen uptake was assessed using a modified version of the protocol used by Doherty *et al.* (2000). A metronome and two separate digital readouts were used to help the tester and the subjects ensure that a constant cadence of 80 rpm was observed for all stages of the test. The test began with three 7-minute exercise bouts of increasing intensity (80W, 120W, and 160W), with 5 minutes rest between bouts. Immediately after the third bout, the intensity was increased by 40W every 2-minutes until subjects reached volitional exhaustion. $\dot{V}O_{2max}$ was determined as the highest 20-breath average $\dot{V}O_2$ observed during the test provided that at least two of the following criteria had been met:

- A plateau in $\dot{V}O_2$ at volitional exhaustion.
- An RER value ≥ 1.10
- A maximum heart rate of 220 – age ($\pm$ 10 $b.min^{-1}$)

8.2.6 Maximal Accumulated Oxygen Deficit

Oxygen consumption during the final two minutes of each of the 7-minute submaximal stages of the maximal oxygen uptake test, together with a fixed y-intercept of 5 $ml.kg^{-1}.min^{-1}$ (Medbø *et al.*, 1988) were used to develop linear regression equations of $\dot{V}O_2$ versus power

output for each subject. The intensity for the MAOD test (110% of the power output required to elicit $\dot{V}O_{2max}$) was calculated by extrapolation of this regression equation.

After the warm-up subjects were given 5-minutes stationary rest before the start of the test. Prior to the test subjects were informed that they should attempt to reach the required cadence of 80 rpm as soon as possible and to maintain this cadence for as long as possible. Two digital readouts and a metronome were used to assist the subjects and the tester. The test was terminated once subjects were no longer able to maintain the required cadence.

Oxygen consumption and heart rate were monitored continuously (breath-by-breath) throughout each test. After allowing 5-s from the start of each test to give subjects time to reach the required cadence, the total oxygen consumption during each test was calculated. Maximal accumulated oxygen deficit (calculated in O_2 equivalents) was determined from the difference between the predicted oxygen demand of the exercise (as determined from the aforementioned regression equation) and the actual oxygen consumption. No adjustment was made in MAOD values for the aerobic component of MAOD (stored oxygen).

8.2.7 Training procedures

Subjects in the experimental group trained for 20 minutes, three times per week, for six weeks. The intensity for the training sessions (70% of the power output required to elicit $\dot{V}O_{2max}$) was determined from the same regression equations used in the MAOD tests. All training was performed on friction-loaded cycle ergometers (Monark, model 814E). Digital readouts, and music played at a fixed tempo of 160 $b.min^{-1}$ were used to assist the subjects to maintain the required cadence of 80 rpm. Each training session was separated by a minimum 24-hour recovery period. Heart rate data were monitored continuously throughout each training session by means of short-range radio telemetry (Sport-tester: Polar Electro Oy, Finland).

Progressive overload during the training period was applied in a manner similar to that employed by Gaiga & Docherty (1995). At the end of the first week of training the flywheel load was increased by 0.1 kg. This intensity was maintained until the mean heart rate during training returned to the level observed during the first week at which point a further 0.1 kg was added to the flywheel. This process was repeated so that by the end of the training

period the mean heart rate response during the final week of training was similar to that recorded during the first week.

8.2.8 Data analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Measures of centrality and spread are presented as means ± SD. The effectiveness of the training programme in maintaining the required intensity was evaluated from a paired t-test. Comparisons between the experimental and control groups on changes in the mean of the performance measures recorded during the intermittent test protocols were evaluated from unpaired t-tests on the pre-post difference scores. The same analyses provided 95% confidence limits for all measures.

8.3 Results

8.3.1 Training Intensity

The training intensity of the experimental group increased, in absolute terms, throughout the training programme from an initial mean power output of 166 ± 21 Watts, to 198 ± 22 Watts in the final week of training. The difference between the training intensity in the final week of training and the predicted intensity based on the post-training $\dot{V}O_2$ regression equations was 4 ± 20 Watts (95% likely range: -9 to 17 Watts).

8.3.2 Anthropometry

Changes in mean body mass and mean percentage body fat in the experimental group, relative to the control group, over the course of the training period were trivial.

8.3.3 Maximal Oxygen Uptake and Maximal Accumulated Oxygen Deficit

Changes in $\dot{V}O_{2max}$ and MAOD over the course of the six-week training period are summarised in Table 8.2. Relative to controls, training resulted in a 10.2% increase in mean $\dot{V}O_{2max}$ (95% likely range: 4.5% to 15.8%). Changes in MAOD over the same period were trivial.

Table 8.2 The influence of six weeks of endurance training on $\dot{V}O_{2max}$ and MAOD.

	Experimental Group		Control Group	
	Pre Training	**Post Training**	**Pre Training**	**Post Training**
$\dot{V}O_{2max}$ ($l.min^{-1}$)	3.65 ± 0.33	4.01 ± 0.27	4.10 ± 0.28	4.09 ± 0.29
MAOD (lO_2 eq)	4.03 ± 0.77	3.98 ± 0.72	4.21 ± 0.90	4.15 ± 0.88

Note: MAOD = Maximal Accumulated Oxygen Deficit; O_2 eq. = Oxygen Equivalents.

8.3.4 Power Output

Figures 8.1 and 8.2 show the mean power output data for each of the 20 sprints during Protocols 1 and 2 respectively in the experimental trials (pre and post training). Relative to the control group, training resulted in substantial increases in all measures of power output (Tables 8.3 and 8.4).

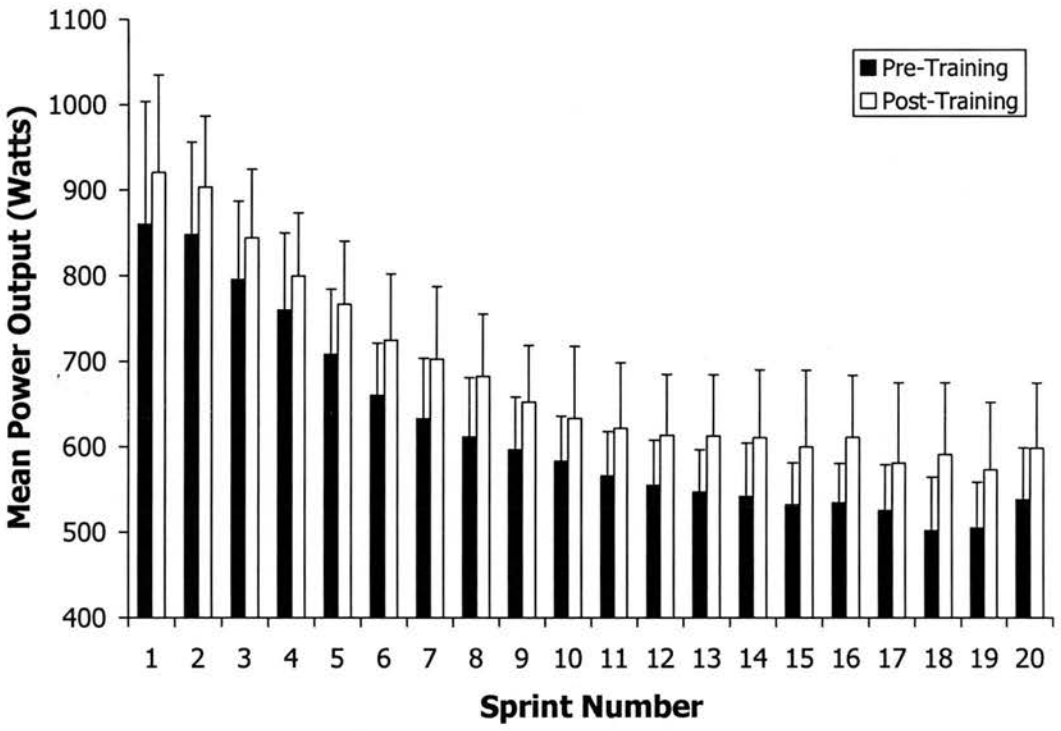


Figure 8.1 Mean power output data during maximal intermittent sprint trials (20 x 5-s work, 10-s rest) before and after 6-weeks of endurance training. Values are means; bars are standard deviations.

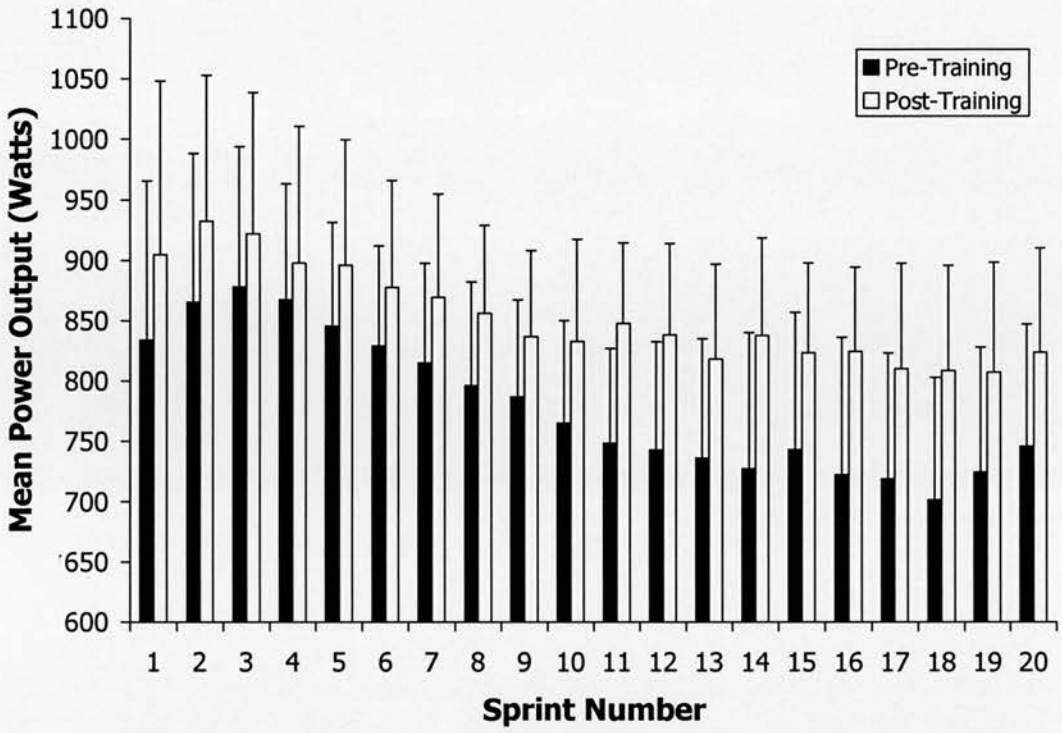


Figure 8.2 Mean power output data during maximal intermittent sprint trials (20 x 5-s work, 30-s rest) before and after 6-weeks of endurance training. Values are means; bars are standard deviations.

Table 8.3 The influence of six weeks of endurance training on power output during 20 x 5-s bouts of all-out cycling interspersed with 10-s rest periods.

	Experimental Group		Control Group		Mean Percentage Change	
	Pre Training	Post Training	Pre Training	Post Training	Mean change (Exp v Con)	95% CL
PP_{max} (Watts)	1088 ± 163	1132 ± 125	1147 ± 160	1106 ± 155	+7.9%	1.0 to 14.8%
PP_{mean} (Watts)	771 ± 86	830 ± 90	831 ± 68	857 ± 87	+4.6%	-0.5 to 9.6%
MP_{max} (Watts)	878 ± 132	938 ± 99	912 ± 114	909 ± 119	+7.5%	0.1 to 14.8%
MP_{mean} (Watts)	620 ± 60	682 ± 71	665 ± 54	684 ± 60	+7.1%	2.2 to 12.0%

Note: PP_{max} = Maximum Peak Power; MP_{max} = Maximum Mean Power; PP_{mean} = Mean Peak Power; MP_{mean} = Mean Mean Power; CI = Confidence Limits; Exp = Experimental; Con = Control.

8.3.5 Fatigue

Table 8.5 shows the mean fatigue scores for the experimental and control groups during the intermittent test protocols. In Protocol 1, the experimental group showed little change in fatigue relative to the control group following the training period. In contrast, fatigue in

Protocol 2 reduced in absolute terms by 4.0% (95% likely range: 0.6 to 7.4%) relative to the control group after training.

Table 8.4 The influence of six weeks of endurance training on power output during 20 x 5-s bouts of all-out cycling interspersed with 30-s rest periods.

	Experimental Group		Control Group		Mean Percentage Change	
	Pre Training	Post Training	Pre Training	Post Training	Mean change (Exp v Con)	95% CL
PP_{max} (Watts)	1122 ± 127	1153 ± 153	1193 ± 165	1176 ± 149	+3.6%	-2.7 to 9.9%
PP_{mean} (Watts)	961 ± 112	1034 ± 99	1072 ± 118	1088 ± 134	+6.4%	-0.2 to 13.0%
MP_{max} (Watts)	916 ± 97	953 ± 114	958 ± 119	962 ± 101	+3.2%	-1.7 to 8.2%
MP_{mean} (Watts)	780 ± 88	853 ± 82	881 ± 92	894 ± 96	+8.2%	2.7 to 13.6%

Note: PP_{max} = Maximum Peak Power; MP_{max} = Maximum Mean Power; PP_{mean} = Mean Peak Power; MP_{mean} = Mean Mean Power; CI = Confidence Limits; Exp = Experimental; Con = Control.

Table 8.5 The influence of six weeks of endurance training on fatigue during 20 x 5-s bouts of all-out cycling with contrasting recovery periods.

	Experimental Group		Control Group	
	Pre Training	Post Training	Pre Training	Post Training
Fatigue (%): Protocol 1[a]	28.8 ± 5.3	27.0 ± 6.03	26.6 ± 4.0	24.3 ± 4.9
Fatigue (%): Protocol 2[b]	14.9 ± 4.2	10.2 ± 3.7	7.8 ± 3.7	7.1 ± 0.9

Note: a = 20 x 5-s work, 10-s rest; b = 20 x 5-s work, 30-s rest.

8.3.6 Physiological Data

Relative to controls, training had little effect on any of the physiological measures ($\dot{V}O_2$, RER, blood lactate, and heart rate) recorded during the intermittent test protocols.

8.3.7 Ratings of Perceived Exertion

In Protocol 1, the experimental group showed little change in the mean RPE response relative to the control group as a result of the training. In contrast, the magnitude of the change in the mean RPE response by the experimental group relative to the control group during Protocol 2 increased substantially throughout the test (Table 8.6).

Table 8.6 The influence of six weeks of endurance training on individual ratings of perceived exertion during 20 x 5-s bouts of all-out cycling interspersed with 30-s recovery periods.

	Experimental Group		Control Group		Mean Percentage Change	
	Pre Training	Post Training	Pre Training	Post Training	Mean Change (Exp v Con)	95% CL
RPE (Sprint 5)	11.4 ± 1.8	10.2 ± 1.8	10.7 ± 2.5	9.7 ± 2.1	-2.2%	18.1 to -22.4%
RPE (Sprint 10)	14.8 ± 1.0	13.3 ± 1.4	12.7 ± 2.5	12.0 ± 1.4	-7.2%	6.5 to -20.9%
RPE (Sprint 15)	16.6 ± 1.4	15.3 ± 1.5	14.0 ± 1.7	14.1 ± 1.6	-9.5%	0.0 to -19.1%
RPE (Sprint 20)	17.8 ± 1.6	16.9 ± 1.7	15.2 ± 1.8	15.7 ± 1.6	-8.2%	-0.3 to -16.2%

Note: CL = Confidence Limit; RPE = Rating of Perceived Exertion; Exp = Experimental; Con = Control.

8.4 Discussion

The main purpose of this investigation was to examine the influence of six weeks of endurance training on maximal sport-specific intermittent performance. As a result of the training intervention, the experimental group showed substantial improvements, relative to controls, in measures of power output in both intermittent test protocols. Although the confidence limits for the true magnitude of those changes in some cases overlap zero, the results support the likelihood that the effects were positive.

In Study III it was observed that measures of maximum power output (PP_{max} and MP_{max}) occur predominantly in the first sprint during Protocol 1, and within the first few sprints in Protocol 2 (see Chapter 6). As such, the improvements in maximum power output observed in this investigation were unlikely to have been influenced by recovery duration. Several possibilities exist to explain the training-induced increases in maximum power output. An increased anaerobic contribution to the sprints is unlikely given the absence of any improvements in MAOD. Moreover, endurance training is reported to have little influence on anaerobic enzyme activity or the concentration of high-energy phosphates (Oscai & Holloszy, 1971; Saltin & Gollnick, 1983). Instead, the improvements in maximum power output were more likely the result of other factors such as an increased aerobic contribution to the sprints, an increased mechanical efficiency, and chance.

The idea of an increased aerobic contribution to the sprints is probable since physiological adaptations associated with endurance training have been shown to result in a faster

adjustment of oxygen uptake to the energy demands of exercise (Carter *et al.*, 2000; Chilibeck *et al.*, 1996; Demarle *et al.*, 2001; Hagberg *et al.*, 1980; Hickson *et al.*, 1978; Norris & Petersen, 1998; Phillips *et al.*, 1995; Yoshida *et al.*, 1992). However, given the relatively small (< 10%) aerobic component of a single short sprint (Bangsbo *et al.*, 2001; Parolin et al., 1999), it is unlikely that a training-induced reduction in the time-course of $\dot{V}O_2$ kinetics would have been sufficient to fully account for the improvements in maximum power output observed in this investigation.

An improved mechanical efficiency could also explain the improvements in maximum power output, particularly since the subjects were not trained cyclists. In effect, despite the relatively low level of resistance applied during the training period, the training stimulus may have been sufficient to facilitate appreciable improvements in maximum power output via neuromuscular improvements in coordination and control. Unfortunately, whilst the training-induced improvements in maximum power output can be reconciled by metabolic and neurological adaptations to the training programme, it is not possible to distinguish the relative contribution made by each of these processes from the data obtained in this investigation.

Although the results support substantial improvements in maximum power output as a result of the training, the magnitude of the changes are largely (with the exception of MP_{max} in Protocol 2) within the coefficient of variation associated with each measure (See Study I). Whilst the improvements in maximum power output may have occurred by chance, the confidence limits allow for the possibility of a substantial effect. Further research with a larger sample size would improve the precision of these estimates.

The factors responsible for the improvements in maximum power output observed in this investigation could also potentially explain the improvements in mean power output. However, the fact that the magnitude of the changes was greater in Protocol 2 than in Protocol 1, suggests that factors associated with the duration of the recovery periods also had an influence on this effect. Longer recovery periods allow for a greater return to homeostasis and an increased ability to maintain power output during successive sprints (Balsom *et al.*, 1992a; Holmyard *et al.*, 1988; Wootton & Williams, 1983).

The most likely explanation for the improvements in mean power output is an elevated PCr contribution to each sprint. Although there is some contradictory evidence (Cooke *et al.*, 1997), most investigations support the view that endurance training is associated with an enhanced rate of post-exercise PCr resynthesis (Bogdanis *et al.*, 1996; Laurent *et al.*, 1992; McCully *et al.*, 1989; McCully *et al.*, 1992; McCully & Posner, 1992; Takahashi *et al.*, 1995; Yoshida & Watari, 1993). With resynthesis rates of approximately 1.3 mmol.kg $dm^{-1}.s^{-1}$ (Gaitanos *et al.*, 1993) the longer recovery periods of Protocol 2 would have allowed a greater manifestation of this effect and explain the differences in between-protocol improvements in measures of mean power output. Although improvements in mean power output could also be explained by training-induced improvements in the rate of post-exercise lactate clearance, with a half-time of approximately nine minutes (Metzger & Fitts, 1987; Sahlin *et al.*, 1976), it is unlikely that this process would have influenced the results.

Another training adaptation that may have influenced the improvements in mean power output is an enhanced rate of post-exercise intracellular inorganic phosphate (P_i) removal. Intracellular P_i accumulation has recently been implicated as one of the major causes of muscular fatigue via its influence on sarcoplasmic reticulum (SR) Ca^{2+} release (Allen *et al.*, 2002; Dahlstedt *et al.*, 2000; Dahlstedt & Westerblad, 2001; Fryer *et al.*, 1995; Kabbara & Allen, 1999). Although corroborative evidence is sparse, endurance training is associated with improvements in off-transient P_i kinetics (Yoshida & Watari, 1993) that may have increased excitation-contraction coupling by enhancing the rate of SR Ca^{2+} release during each sprint.

The idea that the improvements in mean power output were the result of an increased aerobic contribution is compelling considering the magnitude of the improvement in $\dot{V}O_{2max}$ and the lack of improvement in MAOD. However, the experimental group showed little change in $\dot{V}O_2$ relative to the control group during the tests. Endurance training is associated with various adaptations which, in addition to improving $\dot{V}O_{2max}$, also result in a reduced $\dot{V}O_2$ for any absolute exercise intensity (Jones & Carter, 2000). An improvement in exercise economy provides a possible explanation as to why the improvements in power output were not accompanied by any sizeable increases in $\dot{V}O_2$ during the intermittent tests.

Despite the fact that substantial improvements in mean power output were observed in both intermittent test protocols as a result of the training, considerable reductions in fatigue were only evident in Protocol 2. The disparity between the two intermittent test protocols in terms of training-induced changes in fatigue was also reflected in the RPE scores. In effect, individuals who fatigued less as a result of the training also perceived their level of exertion to be less, despite an increase in power output. Once again, the physiological adaptations to the endurance training may have enhanced recovery sufficiently enough during the 30-s recovery periods to facilitate substantial reductions in RPE and fatigue via an increased PCr contribution to the sprints and an enhanced rate of SR Ca^{2+} release.

Finally, in contrast to the changes in maximum power output, the improvements in mean power output (Protocols 1 and 2) and fatigue (Protocol 2) during the intermittent test protocols were considerably larger than their respective test-retest coefficients of variation (see Studies I & II). Although the confidence limits show some overlap with the coefficients of variation, the data support the likelihood that the endurance training resulted in substantial improvements in both measures.

8.5 Conclusions

The ability to produce and maintain high power outputs during prolonged periods of brief maximal intermittent work is an important determinant of performance in many sports. The results of the final investigation of this thesis demonstrate the considerable influence of aerobic fitness in this respect, the magnitude of the effects being largely determined by the duration of the intervening rest periods. Although the precise mechanisms of action require further investigation, the improvements in repeat sprint performance that accompany increases in aerobic fitness are likely to be the result of enhancements in the recovery of power output via improved off-transient inorganic phosphate and PCr kinetics.

9. CONCLUSIONS

9.1 Summary of Thesis

The ability to repeatedly produce and maintain short bursts of high power output is an important determinant of performance during the prolonged periods of play experienced in many sports (e.g. badminton, basketball, hockey, soccer, and squash). Although the activity patterns of such events are extremely complex, the results of this thesis show that laboratory-based simulations of this type of work provide a reliable means of evaluating various cross-sectional and longitudinal investigations. However, the principle aim of this thesis was to investigate the influence of aerobic fitness on performance during this type of work. The results show that aerobic fitness has a considerable effect on the ability to maintain performance during this type of work, the magnitude of which appears to increase with increasing recovery duration. Although the precise mechanisms of action require further investigation, the results of the present thesis combined with evidence from previous research suggests that aerobic enhancements of repeat sprint performance are most likely mediated via improved off-transient PCr and P_i kinetics.

9.2 Directions for Future Research

Although the results of the present thesis support the theory that an enhanced level of aerobic fitness can help to maintain performance during brief maximal intermittent work, the precise mechanisms of this response remain largely speculative. Future research needs to focus on detailed intramuscular examinations of the metabolic response to this type of work, with particular focus on the adaptations that occur as a result of various forms of training. Further advancements in nuclear magnetic resonance imagery techniques provide the most likely means of addressing this issue. In the meantime, intramuscular examinations of the influence of endurance training on both PCr and P_i recovery kinetics would provide valuable information to support the conclusions of the present thesis.

Finally, although the activity patterns of many sports are intermittent in nature, research into training strategies to enhance performance during this type of work is sparse. In particular, despite the need for specificity in training, very little information is available on the effects of multiple sprint training on multiple sprint performance. Further research in this area

combined with an increased knowledge of the metabolic responses to this type of work may help coaches and athletes improve performance in many sports.

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APPENDIX

CONTENTS

APPENDIX 1. HANDOUTS AND FORMS

A1.1 General Guidelines For All Tests

Clothing

Please ensure that suitable clothing is worn for all tests. i.e Shorts, T-shirt/vest, and trainers.

Nutrition

Please avoid eating anything within 1 hour prior to the commencement of each test and avoid caffeinated drinks. Please do not radically change your diet during the programme.

Exercise

Please avoid strenuous exercise within 24 hours prior to the commencement of each test.

Intermittent performance tests

Following appropriate adjustment of the bicycle, you will be given a 5-minute warm-up at 60 rpm with 1.0 kg resistance on the flywheel. The load to be used during the test (0.075 kg.kg body mass $(bm)^{-1}$) will then be applied to the flywheel and you will perform two practice 5-s sprints. Following a further 3-minute rest period the test will begin.

Test no. 1 consists of 20 repeated all-out sprints (5-s) separated by 10-s recovery periods (Total duration: 5-minutes).

Test no. 2 consists of 20 repeated all-out sprints (5-s) separated by 30-s recovery periods (Total duration: 11-mins, 10-s).

The load on the flywheel will remain constant at all times (0.075 kg.kg bm^{-1}) and you will be encouraged to give a maximal effort during each work period and to remain stationary during rest periods. The start of the work and rest periods during the tests will be indicated by a computer-generated bleep. All sprints will be performed in a seated position and from the same starting pedal position.

Your physiological response to the tests will be monitored via several measures:

1. Oxygen consumption: This will be monitored (breath-by-breath) using an on-line gas analysis system.
2. Blood lactate: Small pin-prick blood samples will be obtained from an earlobe for analysis. Samples will be taken at the start, after sprint 10, at the end, and 5-minutes after the test.
3. Heart rate: This will be monitored throughout the tests via the use of 'Polar' heart rate monitors.
4. Rating of perceived exertion (RPE): This will be assessed after every 5 sprints using the 'Borg scale' of perceived exertion.

Graded exercise test to determine maximal oxygen uptake

The determination of $\dot{V}O_{2max}$ will be achieved using a modified graded exercise test designed to additionally provide essential data for the maximal accumulated oxygen deficit (MAOD) test. The test will be performed on a Monarch cycle ergometer at a cadence of 80 rpm. Following a five minute warm-up at 60 rpm (1.0 kg resistance on the flywheel), you will complete three 7-minute sub-maximal bouts of exercise of increasing intensity (80 W, 120 W, and 160 W) with five minutes rest between bouts. Immediately after the third and final bout, the resistance will be increased by 40W every 2-mins until you are no longer able to maintain the required cadence. Heart rate will be monitored throughout the test. Expired air will be analysed breath-by-breath for determination of $\dot{V}O_2$.

Maximal accumulated oxygen deficit (MAOD) test to assess anaerobic capacity

Oxygen consumption ($\dot{V}O_2$) during the final minute of each of the three submaximal workloads during the $\dot{V}O_{2max}$ testing protocol will be used to develop a regression equation to predict the workload corresponding to 110% of your $\dot{V}O_{2max}$. You will be required to cycle at this workload (cadence: 80 rpm) until you are no longer able to maintain the required cadence (usually 2 – 4 minutes). Expired air will be collected continuously throughout the test, using the on-line (breath-by-breath) gas analysis system, to determine total $\dot{V}O_2$. This value will be subtracted from your predicted oxygen demand, calculated from the regression equation, to determine your maximal accumulated oxygen deficit (MAOD).

A1.2 Informed Consent For Study On The Reliability Of Power Output Data During Maximal Intermittent Exercise

The purpose of this study is to determine the reliability of intermittent bouts of short-duration (5-seconds) maximal sprints. The tests will be performed on a cycle ergometer and you will be given instructions on the test protocol prior to commencement of the study.

Following a 5-minute warm-up you will be allowed two practice sprints after which you will be given a further 3-minute rest period before commencement of the test.

During each test you will be required to complete 20 maximal 5-s sprints interspersed with 30-s recovery periods against a resistance equal to 0.075 kg/kg body mass. The start of the work and the rest periods will be indicated by a computer generated bleep.

Although you will be undergoing strenuous exercise, there is very little risk if you are a normal healthy individual.

Individual information obtained from this study will remain confidential. Non-identifiable data will be used for scientific presentations and publications. You may withdraw from the testing at any time. If you have any questions please ask Mark Glaister before signing this consent form.

If you have any additional questions during or after the study, please contact: Mark Glaister (0131 312 6001), University of Edinburgh, Cramond Campus, Cramond Road North, Edinburgh, EH4 6JD.

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED AND YOU HAVE DECIDED TO PARTICIPATE IN THE STUDY.

I have read and understand the above explanation of the purpose and procedures for this test and agree to participate. I also understand that I am free to withdraw my consent at any time.

_____ _____

Signature Witness

_____

Date

A1.3 Informed Consent For Study On The Effects Of Endurance Training On Intermittent Performance – Experimental Group

Many sports require short-duration (≤ 10-s) maximal or near maximal sprints to be repeated regularly over a long period (e.g. Football, Tennis, Netball, Rugby, Badminton, Hockey, etc.). Activities such as these are reported to have both aerobic and anaerobic qualities and as such, physical preparation for these events usually consists of a combination of continuous and interval training. Despite this observation, the approximate contribution from each of these parameters to overall performance remains unresolved. The purpose of this study is to analyse the influence of endurance training on intermittent sprint (5-s) performance typical of that observed in many sports. All tests will be performed on a cycle ergometer and you will be given instructions on the test protocols prior to commencement of the study.

Training

The training programme will consist of 6-weeks of endurance training comprising 3 x 20-min training sessions per week at 70% of the power output required to elicit $\dot{V}O_{2max}$. All training will be performed on Monarch cycle ergometers.

In addition, the following tests will be carried out prior to and following the training period:

1. Intermittent performance test No.1: 20 x 5-s (10-s recovery periods)
2. Intermittent performance test No.2: 20 x 5-s (30-s recovery periods)
3. Graded exercise test to determine $\dot{V}O_{2max}$.
4. Maximal accumulated oxygen deficit (MAOD) test to assess anaerobic capacity.

Although you will be undergoing strenuous exercise, there is very little risk if you are a normal healthy individual.

Individual information obtained from this study will remain confidential. Non-identifiable data will be used for scientific presentations and publications. You may withdraw from the testing at any time. If you have any questions please ask Mark Glaister before signing this consent form.

If you have any additional questions during or after the study, please contact: Mark Glaister (0131 312 6001), University of Edinburgh, Cramond Campus, Cramond Road North, Edinburgh, EH4 6JD.

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED AND YOU HAVE DECIDED TO PARTICIPATE IN THE STUDY.

I have read and understand the above explanation of the purpose and procedures for this test and agree to participate. I also understand that I am free to withdraw my consent at any time.

_____ _____

Signature Witness

_____

Date

A1.4 Informed Consent For Study On The Effects Of Endurance Training On Intermittent Performance – Control Group

Many sports require short-duration (≤ 10-s) maximal or near maximal sprints to be repeated regularly over a long period (e.g. Football, Tennis, Netball, Rugby, Badminton, Hockey, etc.). Activities such as these are reported to have both aerobic and anaerobic qualities and as such, physical preparation for these events usually consists of a combination of continuous and interval training. Despite this observation, the approximate contribution from each of these parameters to overall performance remains unresolved. The purpose of this study is to analyse the influence of endurance training on intermittent sprint (5-s) performance typical of that observed in many sports. All tests will be performed on a cycle ergometer and you will be given instructions on the test protocols prior to commencement of the study.

The following tests will be carried out prior to and following the training period:

1. Intermittent performance test No.1: 20 x 5-s (10-s recovery periods)
2. Intermittent performance test No.2: 20 x 5-s (30-s recovery periods)
3. Graded exercise test to determine $\dot{V}O_{2max}$.
4. Maximal accumulated oxygen deficit (MAOD) test to assess anaerobic capacity.

Although you will be undergoing strenuous exercise, there is very little risk if you are a normal healthy individual.

Individual information obtained from this study will remain confidential. Non-identifiable data will be used for scientific presentations and publications. You may withdraw from the testing at any time. If you have any questions please ask Mark Glaister before signing this consent form.

If you have any additional questions during or after the study, please contact: Mark Glaister (0131 312 6001), University of Edinburgh, Cramond Campus, Cramond Road North, Edinburgh, EH4 6JD.

YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE READ THE INFORMATION PROVIDED AND YOU HAVE DECIDED TO PARTICIPATE IN THE STUDY.

I have read and understand the above explanation of the purpose and procedures for this test and agree to participate. I also understand that I am free to withdraw my consent at any time.

_____ _____

Signature Witness

_____

Date

A1.5 Training History Questionnaire

Name: _____

Please answer the following questions as honestly as possible:

1. How many years have you been actively involved in sport? ____ years.
2. How many sports do you participated in on a regular basis? ____ sports.
3. Which sports (if more than 6, list the main ones)?

   _____

   _____

   _____

   _____

   _____

   _____

4. How many hours a week do you play sport? ____ hours.
5. How many hours a week do you train for sport? ____ hours.

In a typical week, which of the following exercises are performed as part of your training (please tick)?

Long distance running. Please indicate approximate mileage. ____ miles.

Sprinting (number and average distance). ____ no.

____ dist.

Flexibility exercises (hours per week) ____ hours.

Weight training (hours per week) ____ hours.

A1.6 Data Collection Sheet for Intermittent Test No.1 (5-s sprint, 10-s recovery)

- Name: _____
- Date: _____
- Weight _____ kg
- Flywheel Load = _____ kg (0.075 x Body Weight)
- Saddle Height: _____
- Air Temperature = _____ °C
- Relative Humidity = _____ %
- Atmospheric Pressure = _____ mmHg
- VO_2 Data Start Time = _____

Warm-up Instructions

- Fit heart-rate monitor
- Cycle for 5-mins at 60 rpm (1kg resistance on flywheel)

Power Data

- File Name: _____
- Problem Sprints: _____

$\dot{V}O_2$ Data

- File Name: _____

Heart Rate Data

- File Name: _____

RPE

- After Sprint No.5: _____
- After Sprint No.10: _____
- After Sprint No.15: _____
- After Sprint No.20: _____

Blood Lactate

- Start: _____ $mmol.l^{-1}$
- After Sprint No.10: _____ $mmol.l^{-1}$
- End: _____ $mmol.l^{-1}$
- 5-mins Post Test: _____ $mmol.l^{-1}$

A1.7 Data Collection Sheet for Intermittent Test No.2 (5-s sprint, 30-s recovery)

- Name: _____
- Date: _____
- Weight _____ kg
- Flywheel Load = _____ kg (0.075 x Body Weight)
- Saddle Height: _____
- Air Temperature = _____ °C
- Relative Humidity = _____ %
- Atmospheric Pressure = _____ mmHg
- $\dot{V}O_2$ Data Start Time = _____

Warm-up Instructions

- Fit heart-rate monitor
- Cycle for 5-mins at 60 rpm (1kg resistance on flywheel)

Power Data

- File Name: _____
- Problem Sprints: _____

$\dot{V}O_2$ Data

- File Name: _____

Heart Rate Data

- File Name: _____

RPE

- After Sprint No.5: _____
- After Sprint No.10: _____
- After Sprint No.15: _____
- After Sprint No.20: _____

Blood Lactate

- Start: _____ $mmol.l^{-1}$
- After Sprint No.10: _____ $mmol.l^{-1}$
- 5-mins Post Test: _____ $mmol.l^{-1}$

A1.8 Data Collection Sheet for Maximal Oxygen Uptake Test

- Name: _____
- Date: _____
- Saddle Height: _____
- Air Temperature = _____ °C
- Relative Humidity = _____ %
- Atmospheric Pressure = _____ mmHg

Heart Rate Data

- File Name: _____

$\dot{V}O_2$ Data

- File Name: _____

Stages (cadence = 80 rpm)

1. 7-mins at 80 W (1 kg on basket)
2. 5-mins recovery
3. 7-mins at 120 W (1.5 kg on basket)
4. 5-mins recovery
5. 7-mins at 160 W (2.0 kg on basket)
6. Increase load by 40 W (0.5 kg) every 2-mins

Time to end of test: _____ mins

Final power output: _____ Watts

A1.9 Data Collection Sheet for MAOD Test

- Name: _____
- Date: _____
- Saddle Height: _____
- Flywheel Load: _____ kg
- Air Temperature = _____ °C
- Relative Humidity = _____ %
- Atmospheric Pressure = _____ mmHg

Skinfold Measures

Chest:	_____ mm	_____ mm
Midaxilla:	_____ mm	_____ mm
Tricep:	_____ mm	_____ mm
Subscapula:	_____ mm	_____ mm
Abdomen:	_____ mm	_____ mm
Suprailiac:	_____ mm	_____ mm
Thigh:	_____ mm	_____ mm

Warm-up Procedures

- 5-mins at 60rpm (1kg resistance on flywheel)
- 5-mins stationary rest

Heart Rate Data

- File Name: _____

$\dot{V}O_2$ Data

- File Name: _____

Subject pedals at a cadence of 80 rpm.

Time at start of test: _____ mins

Time at end of test: _____ mins

Recovery Lactate: _____ $mmol.l^{-1}$

APPENDIX 2. PUBLISHED RESEARCH ARTICLES

A2.1 Reliability of power output during short-duration maximal-intensity intermittent cycling.

Mark Glaister, Michael H. Stone, Andrew M. Stewart, Michael Hughes & Gavin L. Moir.

Journal of Strength & Conditioning Research (2003). In Press.

ABSTRACT

Purpose: The aims of the present study were: a) to determine the number of familiarisation trials required to establish a high degree of reliability in measures of power output during maximal intermittent cycling; and b) to examine the reliability of those same measures once familiarisation had been established. **Methods:** On separate days over a three week period, two groups of seven recreationally active men completed eight trials of one of two maximal (20 x 5-s) intermittent cycling tests with contrasting recovery periods (10-s or 30-s). **Results:** Significant ($p < 0.05$) between-trial differences were detected in post-hoc tests involving trials 1 and 2 only. Within-subject test-retest reliability was therefore assessed across trials 3 – 8. Apart from values of maximum power output in Protocol 1 (10-s recovery periods), all remaining measures of power output showed high degrees of within-subject test-retest reliability (coefficient of variation (CV): 2.4 – 3.7%). **Conclusions:** The results of the present study indicate that in subjects unfamiliar with maximal intermittent cycling, high degrees of reliability in many performance measures can be achieved following the completion of two familiarisation trials.

INTRODUCTION

Short-duration, high-intensity, intermittent exercise represents an activity pattern common to many sports (e.g. badminton, basketball, soccer, and rugby). Research into the physiological response to this type of work has increased considerably in recent years, with many authors examining repeated bouts of brief (≤ 10-s) high-intensity work typical of those experienced in many sports (Balsom, 1995; Brooks *et al.*, 1990; Christmass *et al.*, 1999; Gaitanos *et al.*, 1993; Hamilton *et al.*, 1991; Holmyard *et al.*, 1988 Wootton & Williams, 1983). Although laboratory based assessments of intermittent work fail to truly replicate the demands of

competitive sports performance, at present they provide the best means of directly assessing the physiological response to this type of work. Despite this observation, research to date on the reliability of tests designed to analyse intermittent performance is limited. Moreover, whilst it may be common practice for researchers to conduct familiarisation trials prior to an investigation to reduce the influence of learning effects on results, information on the influence of familiarisation on test-retest reliability is limited.

The first aim of the present study was to determine the number of familiarisation trials required to establish a high degree of reliability in measures of power output during two distinct maximal-effort intermittent cycling tests. The tests were designed to simulate the range of work:rest (W:R) ratios often experienced in sports such as badminton (Docherty, 1982; Liddle *et al.*, 1996), soccer (Mayhew & Wenger, 1985; Reilly, 1997), rugby (Brewer & Davis, 1995; Docherty *et al.* 1988), and squash (Docherty, 1982; Montpetit, 1990). The second aim of the present study was to examine the reliability of those same performance measures once familiarisation had been established.

METHODS

Experimental Approach to the Problem

All subjects completed eight trials of one of the maximal intermittent test protocols to provide sufficient data for familiarisation and reliability analysis. Protocol 1 consisted of twenty 5-s sprints separated by 10-s recovery periods (W:R = 1:2). Protocol 2 consisted of twenty 5-s sprints separated by 30-s recovery periods (W:R = 1:6). All testing was conducted over a three-week period and all trials were separated by a minimum 24-hour recovery period. Subjects were instructed to maintain their normal diet throughout the testing period, to avoid food and drink in the hour before each trial, and to refrain from strenuous exercise 24-hours before each trial. Familiarisation was quantified using the statistical procedures outlined by Martin *et al.* (2000). Once the time course of familiarisation had been established, within-subject test-retest reliability was examined over the remaining trials.

Subjects

Two groups of seven recreationally active men volunteered for the study. Ethical approval for the study was granted by the University of Edinburgh and all subjects gave their written

informed consent prior to participation. The means ± standard deviation (SD) for age, height, and body mass are presented in Table 1.

Table 1. Subject characteristics

Protocol	Age (years)	Height (cm)	Body mass (kg)
1	25.0 ± 3.7	176.5 ± 8.1	70.7 ± 3.6
2	25.6 ± 4.1	177.8 ± 6.7	72.5 ± 6.2

Equipment

All trials were conducted on a friction-loaded cycle ergometer (Monark, model 814E), which was fitted with standard toe-clips and straps and secured to the floor of the laboratory. The flywheel rim of the ergometer was modified by the addition of 90 black-white strips that were interfaced via a photo-reflective opto-sensor with a computer to enable high-frequency logging of the flywheel angular velocity. The flywheel resistance for all trials was set at 0.075 kg.kg body mass^{-1} and flywheel rotations were sampled at a frequency of 18.2 Hz. The ergometer was calibrated prior to every trial.

Testing Procedures

Apart from the difference in the amount of recovery between each sprint (10-s versus 30-s), the methodology for both intermittent test protocols was the same. Before the start of each trial, subjects completed a 5-minute warm-up at 60 revolutions per minute against a flywheel resistance of 1.0 kg. The saddle height for the warm-up and the trials was determined for each subject before the first trial and remained constant for all subsequent trials. Subjects were instructed to remain seated in the saddle for the duration of each trial, to always start each sprint with the pedals in the same position, to remain stationary during recovery periods, and to always give a maximal effort. Immediately following the warm-up, subjects performed two 5-s practice sprints against the resistance to be used during the trial. After a further 3-minute stationary rest period, the trial began. Subjects were given a 5-s countdown before each sprint, the start and finish of which were indicated by a computer-generated signal. Subjects were verbally encouraged to give a maximal effort during every sprint.

The power output during each sprint was corrected for flywheel inertia in accordance with the procedures outlined by Lakomy (1986) and averaged over 1-s intervals. From these data,

the following performance measures were determined for each sprint: peak power output (PP), mean power output (MP), and time to peak power (TPP). Power output data across each intermittent test protocol were derived as measures of maximum PP (PP_{max}), maximum MP (MP_{max}), mean PP (PP_{mean}), mean MP (MP_{mean}), and mean TPP (TPP_{mean}).

Data analysis

All statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS for Windows, SPSS Inc.). Measures of centrality and spread are presented as means ± SD. The *n* size used in the present study was determined from a power value of 0.8, an effect size based on previous research (Fitzsimons *et al.*, 1993), and an α level of 0.05. To examine the process of familiarisation, differences in the performance measures of maximum power output (PP_{max} and MP_{max}) were evaluated with a one-way repeated measures analysis of variance (ANOVA). If significant ($p < 0.05$) between-trial differences were observed, a Tukey post-hoc analysis was used to determine where those differences occurred. After determining the number of trials required to limit the effects of familiarisation, measures of within-subject variation (coefficient of variation, CV) were derived from a two-way ANOVA as described by Schabort *et al.* (1999). Power output or TPP_{mean} was the dependent variable in the model, the identity of the subjects was a random effect, and the identity of the trial was a fixed effect. Retest correlations were derived from the ANOVA as intraclass correlation coefficients (ICC) using the method described by Bartko (1966). Confidence limits (95%) for CV and ICC were calculated using the methods outlined by McGraw & Wong (1996) and Tate & Klett (1959).

RESULTS

Familiarisation

Mean trial scores of PP_{max} are presented in Figure 1. Similar trends were observed between values of MP_{max}. Significant between-trial differences in these variables were detected in post-hoc tests involving trials 1 and 2 only.

Reliability

As a result of the above data, reliability was assessed over the last 6 trials of each protocol. Means ± SD of all power data (including TPP) along with CV, ICC and associated 95% confidence limits (CL) are presented in Tables 2 - 4.

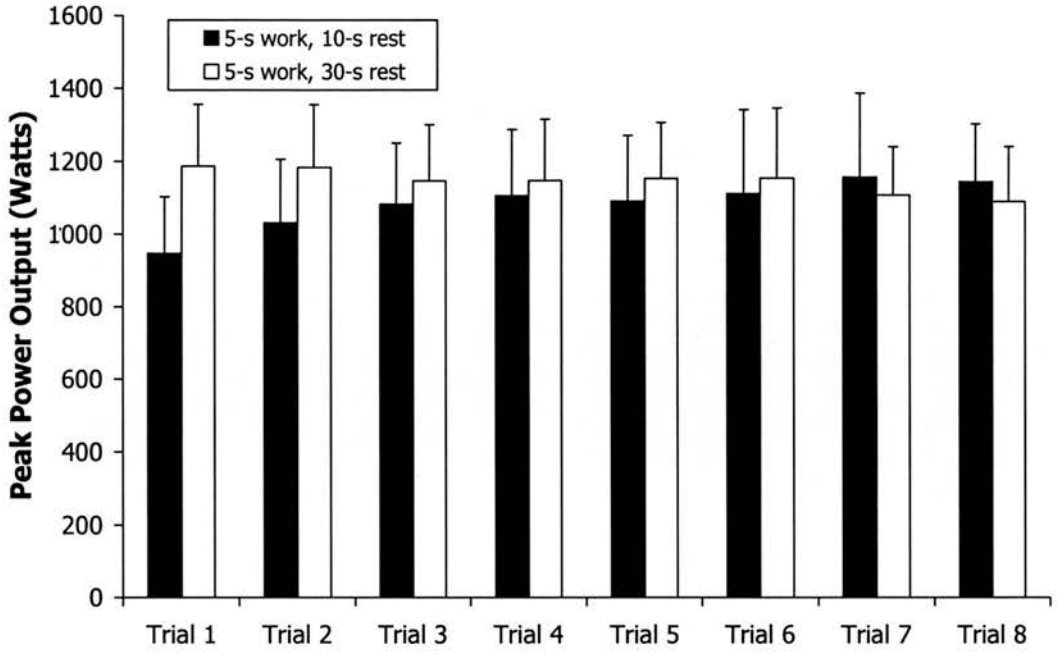

Figure 1. Peak power output data during maximal intermittent cycling trials using different work to rest ratios. Values are means; bars are standard deviations.

Table 2. Power output data from intermittent test protocol 1

	Peak Power Data (Watts)		**Mean Power Data (Watts)**	
	Maximum Peak Power	**Mean Peak Power**	**Maximum Mean Power**	**Mean Mean Power**
Means	1114	803	895	644
SD	*183*	*95*	*162*	*85*
CV	8.1	3.3	8.4	3.4
Lower CL	*6.5*	*2.7*	*6.7*	*2.7*
Upper CL	*10.8*	*4.4*	*11.2*	*4.6*
ICC	0.80	0.93	0.83	0.94
Lower CL	*0.57*	*0.81*	*0.62*	*0.83*
Upper CL	*0.96*	*0.98*	*0.96*	*0.99*

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient; CL = 95% Confidence limits.

Table 3. Power output data from intermittent test protocol 2

	Peak Power Data (Watts)		Mean Power Data (Watts)	
	Maximum Peak Power	**Mean Peak Power**	**Maximum Mean Power**	**Mean Mean Power**
Means	1132	1033	889	824
SD	*151*	*141*	*116*	*109*
CV	3.7	3.5	2.4	2.6
Lower CL	*3.0*	*2.8*	*1.9*	*2.1*
Upper CL	*5.0*	*4.7*	*3.2*	*3.5*
ICC	0.93	0.94	0.97	0.97
Lower CL	*0.83*	*0.85*	*0.92*	*0.91*
Upper CL	*0.99*	*0.99*	*0.99*	*0.99*

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient; CL = 95% Confidence limits.

Table 4. Mean time to peak power data from intermittent test protocols

	Mean Time to Peak Power Data (seconds)	
	Protocol 1	**Protocol 2**
Means	3.59	3.71
SD	*0.40*	*0.39*
CV	8.8	6.4
Lower CL	*7.0*	*5.1*
Upper CL	*11.8*	*8.5*
ICC	0.51	0.63
Lower CL	*0.20*	*0.33*
Upper CL	*0.85*	*0.90*

Note: CV = Coefficient of variation; ICC = Intraclass correlation coefficient; CL = 95% Confidence limits.

DISCUSSION

Knowledge of the familiarisation process and within-subject variation associated with any measure of human performance is essential for the evaluation of the effects of experimental manipulations. Despite this observation, research into the influence of the familiarisation process on test-retest protocols in sports science is sparse. The results of the present study corroborate previous reports suggesting that in subjects unfamiliar with tests of all-out cycling, a minimum of two familiarisation trials are required to establish a high degree of reliability in measures of power output (Capriotti *et al.*, 1999; Martin *et al.*, 2000).

After taking the familiarisation process into account, within-subject variation between trials was assessed across trials 3 – 8. Apart from PP_{max} and MP_{max} in Protocol 1 (Table 2), all remaining measures of power output (Tables 2 & 3) showed high levels of test-retest reliability across both intermittent test protocols. Although the confidence limits allow for the possibility of slight fluctuations in the true magnitude of the data, the results corroborate previous reports of high levels of test-retest reliability in this type of intermittent work (Capriotti *et al.*, 1999; Fitzsimons *et al.*, 1993). Differences between the two intermittent test protocols in terms of within-subject variability in measures of PP_{max} and MP_{max} (Tables 2 & 3) are difficult to elucidate. Although subject motivation was a possible confounding factor, increases in the mean values of PP_{max} (see Figure 1) and MP_{max} during the first three trials of Protocol 1 suggests that a lack of subject motivation was not a cause for concern.

Research into the reliability of power output data during single bouts of maximal sprint cycling (≤ 30-s) suggests that the reliability of mean power output data is superior to peak power output data (Hopkins *et al.*, 2001). Although the reliability of mean power output relative to peak power output was similar in Protocol 1 (Table 2), overall the results of the present study suggest that greater precision in single trials, and more effective monitoring of changes between trials, can best be achieved through the use of mean power output data.

Although the reliability of TPP has previously been examined during single bouts of maximal sprint cycling (≤ 30-s) (Nicklin, *et al.*, 1990; Williams *et al.*, 1988), the present study appears to be the first to examine test-retest reliability in measures of TPP during intermittent work. Despite the moderate degrees of test-retest reliability shown (Table 4), the confidence limits allow for the fact that the true magnitude of the degree of reliability could be anything from poor to good. Further research with a larger sample size would improve the accuracy of these estimates.

PRACTICAL APPLICATIONS

Tests of repeat sprint ability are becoming increasingly commonplace as a means of evaluating the effects of various experimental interventions on the performance capabilities of team sport players. The results of the present study suggest that in subjects unfamiliar with such tests, a minimum of two practice trials are required to reduce the associated

learning effects. Once familiarisation has been established, most measures of repeat sprint performance can be assessed with a high degree of test-retest reliability.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Dr. Simon Coleman for his invaluable help in developing the intermittent sprint tests.

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